European Commission

JRC TECHNICAL REPORT

The operation of the European Power System in 2016

A benchmarking study with METIS

Kanellopoulos K. Kavvadias K, Careri F, De Felice M., Busch S., Hidalgo Gonzalez I.

2019

EUR 30008 EN

EU Science Hub
https://ec.europa.eu/jrc

JRC119053

EUR 30008 EN

PDF ISBN 978-92-76-14098-6 ISSN 1831-9424 doi: 10.2760/434010

Luxembourg: Publications Office of the European Union, 2019

How to cite this report: Kanellopoulos, K., Kavvadias, K., Careri, F., De Felice, M., Busch, S. and Hidalgo Gonzalez, I., The operation of the European Power System in 2016, EUR 30008 EN, Publications Office of the European Union, Luxembourg, 2019, ISBN 978-92-76-14098-6 (online), doi:10.2760/434010 (online), JRC119053.

Contents

Authors

Kanellopoulos, K.

Kavvadias, K.

Careri, F.

De Felice, M.

Busch, S.

Hidalgo González, I.

Abstract

The present report presents the process of simulating the operation of the European power system in its current configuration with METIS. The power system was modelled for 2016 and the results were compared to the relevant published ENTSO-E data. The version of METIS used in this activity was v1.4.

1 Introduction

The present study explores the ability of the METIS model to reproduce the actual operation of the power system in 2016.
This is accomplished by modelling with METIS the European power system in its present state. A scenario (which henceforth will be called "context") was created in METIS to represent the power system in Europe (EU28 and Norway, Switzerland, and the countries of the western Balkans). The current context was calibrated with available historical data from 2016 and the simulation results were benchmarked against the historical actual operation of the power system and the day-ahead market, based on the information published by ENTSOE.
Section 2 provides detailed information on the sources and data used in the current context and describes the input adjustments required in order to reduce inconsistencies between hourly and annual data, as well as the calibration process in order to align the input and results to the actual operation of the power system in the modelled areas during 2016.
Section 3 presents the results of the simulations benchmarked against observed data published by ENTSOE for 2016.
Section 4 provides the conclusions of the present work and the work in planning.

2 The power system context

The current section presents the data used and the steps taken to generate a context in METIS that closely simulates the operation of the current power system in Europe (EU28 and Norway, Switzerland, and the countries of the Western Balkans). The "current context" was calibrated with available historical data from 2016.
The first step for creating a context in METIS consists of collecting, validating and preparing the input files used in the Artelys Crystal environment, the interface to the METIS model used for handling the data, launching the simulations, and displaying and retrieving outputs. The data required are physical assets (power plants, transmission network, etc.), prices (commodity prices and CO2 price) and energy and availabilities (time series of renewable generation, demand, hydro inflows, etc.).

2.1 Physical assets

The Physical assets include the infrastructure in the power system, namely the generating fleets and the interconnections.

2.1.1 Thermal power plants

The thermal power plant fleets for the "Current context" where created bottom-up from the open power plant dataset in the JRC-PPDB[1] database. This dataset contains all the major power plants reported by ENTSO-E on the transparency platform, complemented with available information from national sources where data were unavailable (Malta, Cyprus, Croatia) or incomplete (Spain and the United Kingdom). Table 1 provides the installed capacity allocation into the various technologies and respective classes considered.

Table 1. Installed capacity of fossil fuel technologies (GW) in the simulated area

Fleets	Installed capacity per technology class								
	E class	F class	G/H class	Modern	Standard	Subcri-tical	Supercri-tical	IGCC	Total (GW)
CCGT fleet	5.8	133.5	19.8						159
Coal fleet						67.1	27.9	2.8	97.7
Gas fleet						10.2	1.0		11.2
Lignite fleet						43.9	12.1		56.0
OCGT fleet				1.7	9.4				11.0
Peat fleet						0.8			0.8
Shale oil fleet						2.1	0.2		2.3
	5.8	133.5	19.8	1.7	9.4	124.1	41.1	2.8	338.1

The power plants were allocated into technology classes on the basis of the assessed thermal efficiency, which was in turn based either on real efficiency calculated from actual generation and CO_2 emissions reported on the Transparency Platform of ENTSO-E and IPCC respectively.

Fleet technical characteristics (efficiency, minimum stable load, ramping capability and minimum time off), are estimated as the weighted averages of the respective characteristics of the individual plants belonging to each technology category. Table 2 provides the classification criteria (based on the thermal and the fuel to allocate units to their respective classes.

[1] https://data.jrc.ec.europa.eu/dataset/9810feeb-f062-49cd-8e76-8d8cfd488a05

Table 2. Efficiencies of the different thermal technologies

Technology	Efficiency	Category	Fleets
Steam turbine	<36%	Subcritical	Coal, Lignite
Steam turbine	>36%	Supercritical	Coal, Lignite
Combined cycle	<45%	E class	CCGT
Combined cycle	>45% & <54%	F class	CCGT
Combined cycle	>54%	G/H class	CCGT
Gas turbine	<36%	Standard	OCGT
Gas turbine	>36%	Modern	OCGT

2.1.2 Hydro plants

In the area considered (EU-28, Norway, Switzerland and Western Balkans) there is a significant amount of hydro capacity installed, 209 GW, of which 74% is in the EU, 22% in Norway and Switzerland, and 4% in the Western Balkans.

Within the EU, 71% of the capacity is installed in France (25 GW), Italy (22 GW), Spain (20 GW), Sweden (16 GW), Austria (14 GW) and Germany (11 GW). Hydro capacity is negligible in Denmark, Estonia, Hungary, and the Netherlands

In the Western Balkans hydro capacity amounts to 8.5 GW and hydropower is a key element of the power system in this area.

The current context considers three hydropower technologies:

— Water reservoirs: units (usually large) that store water in a reservoir and generate when the water is released.

— Run-of-river and poundage: units with no significant storage capacity that generate power continuously depending on the water flow.

— Pumped storage: units consisting of reservoirs and different levels. The water is pumped to the upper reservoir when there is surplus energy or the price is low.

The information on hydropower plants is available from different sources:

— The JRC power plant database (JRC-PPDB), which contains information on individual units with capacity above 100 MW.

— ENTSO-E Transparency Platform[2] and Statistical Factsheets[3].

— EURELECTRIC-VGB Hydropower factsheets[4].

— Geth et al. 2015[5], with an overview of large-scale stationary electricity storage plants in Europe (as of 2015).

— EUROSTAT[6].

— IRENA hydropower statistics[7].

The classification of the hydro plants is different in each source. For instance, EUROSTAT considers two groupings but there is no clear correspondence between them: i) by size: hydro plants below 1 MW, in the range 1-10 MW or above 10 MW, and ii) by activity: main activity producers and autoproducers of hydro, mixed, and pure pumped hydro. EURELECTRIC-VGB figures are directly based on EUROSTAT and only distinguish between pumped units and the rest (mixing reservoirs with run-of-river units). Finally, IRENA makes a distinction between pumped storage units, mixed plants, and renewable hydro.

[2] https://transparency.entsoe.eu/.
[3] https://www.entsoe.eu/publications/statistics-and-data/#statistical-factsheet.
[4] https://www.vgb.org/en/hydropower_fact_sheets_2018.html.
[5] F. Geth, T. Brijs, J. Kathan, J. Driesen, R. Belmans. An overview of large-scale stationary electricity storage plants in Europe: current status and new developments. Renew Sustain Energy Rev, 52 (2015), pp. 1212-1227, 10.1016/j.rser.2015.07.145.
[6] Table [nrg_113a] available at: http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nrg_113a&lang=en.
[7] https://www.irena.org/hydropower.

In view of the discrepancies, a comparison of the different sources has been carried out in order to select the most appropriate figures. Table 3 shows the hydro capacities used in the "Current context" (2016), by country and technology.

Table 3. Hydro capacity by country and technology (MW)

Country	Hydro Pumped Storage	Hydro Run-of-river and poundage	Hydro Water Reservoir	Total
Albania	0	0	2 011	2 011
Austria	5 231	5 521	2 937	13 689
Belgium	1 310	115	0	1 425
Bosnia and Herzegovina	420	0	1 746	2 166
Bulgaria	1 013	630	1 580	3 223
Croatia	293	457	1 455	2 205
Czech Republic	1 172	335	755	2 262
Denmark	0	10	0	10
Estonia	0	6	0	6
Finland	0	3 250	0	3250
France	7 135	8 844	9 538	25 517
Germany	6 727	3 854	719	11 300
Greece	699	223	2 470	3 392
Hungary	0	28	29	57
Ireland	292	237	0	529
Italy	7 307	10 605	4 386	22 298
Latvia	0	1 565	0	1 565
Lithuania	900	127	0	1 027
Luxembourg	1 296	17	17	1 330
Montenegro	0	0	651	651
Netherlands	0	37	0	37
North Macedonia	0	660	0	660
Norway	1 536	1 449	28 849	31 834
Poland	1 789	419	177	2 385
Portugal	2 571	2 873	1 516	6 960
Romania	357	2 632	3 745	6 734
Serbia	614	2 008	408	3 030
Slovakia	916	1 272	336	2 524
Slovenia	180	1 113	0	1 293
Spain	6 016	2 741	11 299	20 056
Sweden	99	0	16 367	16 466
Switzerland	2 589	4 023	8 194	14 806
United Kingdom	2 744	1 835	0	4579
Total	53 206	56 887	99 184	209 277

The spatial resolution is limited to one node per country, resulting in a simplified representation of the reservoir hydro generators as one plant and one reservoir. Therefore an assumption regarding the synchronously available capacity is required. This was adjusted by assuming a maximum availability based on the 10 hours with the highest observed generation of the hydro fleet in each country. Table 4 provides the availability parameter used in the current context for 2016.

Table 4. Availability parameter used in the hydro assets

Country	Availability
FI	100%
EL	73%
NO	86%
SE	79%
IT	45%
FR	55%
BG	63%
ES	93%
CH	61%
DE	92%
PT	86%
RO	41%

Figures 1 and 2 illustrate the impact of hydro reservoir assets to operate with a much flatter profile, compared to the actual observed operation.

Figure 1. Impact of a low availability factor on the Italian hydro fleet during the first 2 weeks of January 2016

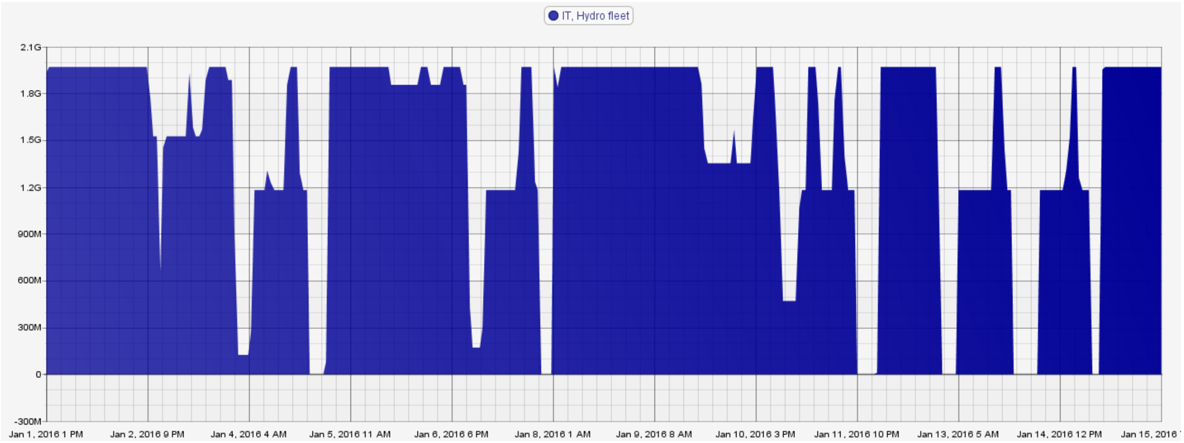
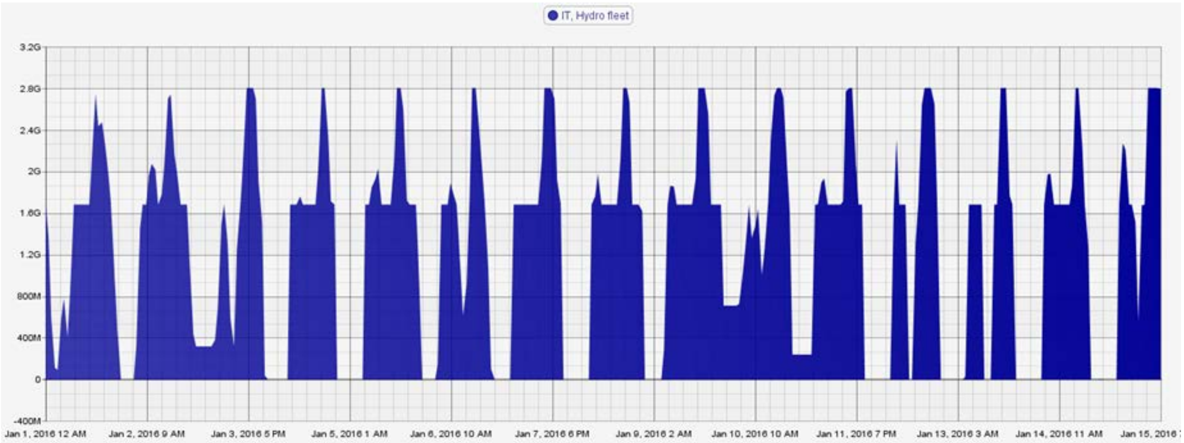


Figure 2 The Italian hydro fleet dispatching with a higher availability



2.1.3 Renewable fleets

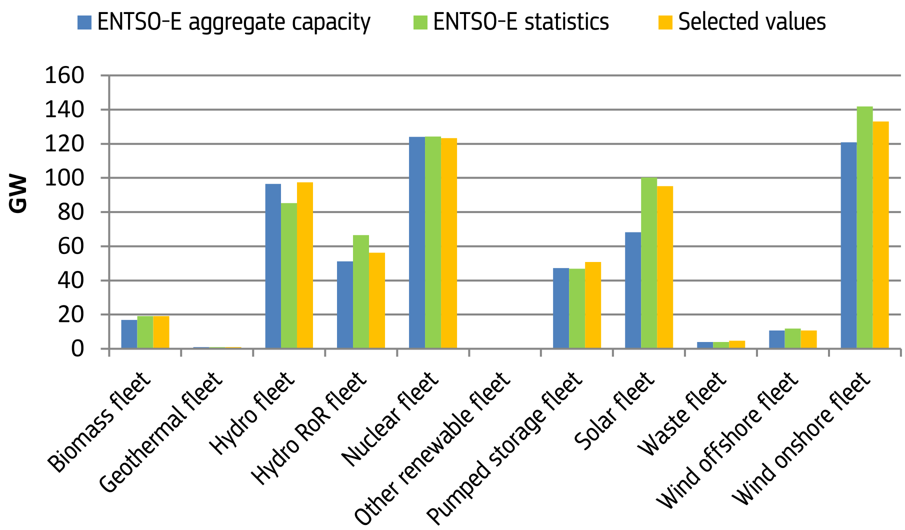
The renewable fleet capacities were defined based on the comparison of three different ENTSO-E sources (namely the aggregate capacities from the transparency platform, the power statistics[8], and the latest winter outlook (2017)) with EUROSTAT, IRENA, and national sources where available or deemed necessary (Spain, UK).

The values selected after comparing the available sources are provided in Table 5, while a comparison between values reported either as aggregate capacities in the transparency platform or Power Statistics[7] is provided in Figure 3.

Table 5. Renewable and nuclear capacity by year and technology (GW) in the simulated area

Renewable and nuclear Fleets	2016	2017	2018
Biomass fleet	19.1	20.1	20.5
Geothermal fleet	1.0	1.0	1.0
Hydro fleet	97.4	97.4	97.4
Hydro RoR fleet	56.2	56.2	56.2
Nuclear fleet	123.2	121.5	121.5
Other renewable fleet	0.2	0.2	0.2
Pumped storage fleet	50.8	50.8	50.8
Solar fleet	95.2	102.3	104.5
Waste fleet	4.7	4.6	5.0
Wind offshore fleet	10.6	12.2	14.5
Wind onshore fleet	133.1	143.4	154.1
Total	591.6	609.9	625.8

Figure 3 Installed capacity 2016



The installed capacity of thermal and renewable generation at country level is provided in Table 14 in Annex 1.

[8] https://www.entsoe.eu/data/power-stats/

2.1.4 Cross-border transmission capacity

Cross border transmission capacity was defined as the maximum values from the ENTSO-E Transparency Platform[9] time series. Since cross-border transmission capacity is traded differently according to the border, the following time series were used as source:

(a) Forecast week-ahead Net Transfer Capacities.

(b) Forecast day-ahead Net Transfer Capacities is case the values in (a) are not available for the relevant border.

(c) Cross border physical flows (according to 12.1 Reg. (EU) 543/2013) in case the values in (a) and (b) are not available for the relevant border.

Table 6 reports the values of maximum NTC values per border, expressed in MW.

Table 6. Maximum NTC values per border (MW)

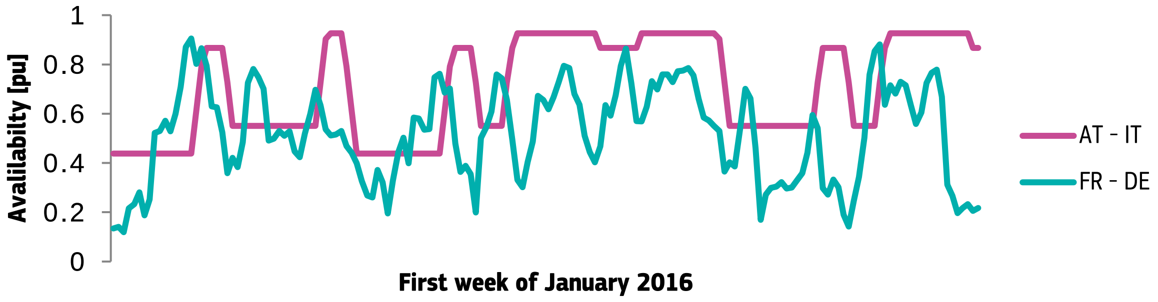
Link	NTC max	Link	NTC max	Link	NTC max	Link	NTC max
AL - EL	250	DE - SE	615	HU – RO	700	PL - DE	275
AL - RS	250	DK - DE	2 035	HU - RS	1 000	PL - LT	492
AT – CH	1 200	DK - NO	1 632	HU - SK	1 000	PL - SE	554
AT – CZ	900	DK - SE	2 490	HU - UA	450	PL - SK	550
AT - DE	1 503	EE - FI	1 016	IE - UK	500	PT - ES	3 900
AT - HU	800	EE - LV	879	IT - AT	145	RO - BG	300
AT - IT	340	ES - FR	3 100	IT - CH	1 910	RO - HU	700
AT - SI	950	ES - PT	3 400	IT - FR	1 160	RO - RS	700
BA - HR	1 800	FI - EE	1 016	IT - GR	500	RO - UA	100
BA - ME	665	FI - NO	72	IT - MT	208	RS - AL	250
BA - RS	600	FI - SE	2 300	IT - SI	680	RS - BA	600
BE - FR	1 600	FR - BE	2 600	LT - LV	684	RS - BG	200
BE - NL	1 501	FR - CH	3 200	LT - PL	489	RS - HR	600
BG - EL	700	FR - DE	4 255	LT - SE	700	RS - HU	1 000
BG - MK	500	FR - ES	3 500	LV - EE	879	RS - ME	700
BG - RO	300	FR - UK	2 000	LV - LT	1 234	RS - MK	700
BG - RS	300	FR - IT	3 459	ME - BA	689	RS - RO	800
CH - AT	1 200	UK- FR	2 000	ME - RS	700	SE - DE	615
CH - DE	4 000	UK- IE	530	MK - BG	51	SE - DK	1 980
CH - FR	1 400	UK- NIE	450	MK - GR	450	SE - FI	2 700
CH - IT	4 532	UK- NL	1 016	MK - RS	400	SE - LT	700
CZ - AT	800	GR - AL	250	MT - IT	0	SE - NO	3 995
CZ - DE	2 800	GR - BG	400	NIE - UK	295	SE - PL	604
CZ - PL	900	GR - IT	500	NL - BE	1 501	SI - AT	950
CZ - SK	2 000	GR - MK	400	NL - DE	2 753	SI - HR	1 500
DE - AT	2 725	GR - TR	326	NL - UK	1 016	SI - IT	802
DE - CH	2 000	HR - BA	1 000	NL - NO	700	SK - CZ	1 200
DE - CZ	800	HR - HU	1 000	NO - DK	1 632	SK - HU	1 200
DE - DK	2 100	HR - RS	600	NO - FI	121	SK - PL	500
DE - FR	2 966	HR - SI	1 500	NO - NL	700	TR - GR	50
DE - NL	3 818	HU - AT	800	NO - SE	3 695	UA - HU	650
DE - PL	2 231	HU - HR	1 200	PL - CZ	900	UA - RO	550

In order to be able to compare the results of the simulation with historical values in 2016, the hourly profile of cross-border capacity availabilities in METIS, reported as *per unit* values, have been set to match the hourly

[9] https://transparency.entsoe.eu/

cross border capacity time series from ENTSO-E Transparency Platform. In the *per unit* system, quantities are expressed as a fraction of a defined base quantity: in this case, to the values reported in Table 6.
Figure 4 shows a sample of availability of cross-border capacities for two selected borders (AT-IT and FR-DE) for the first week of January 2016.

Figure 4 Availability of cross-border capacities (AT-IT, FR-DE), first week of January 2016



The real transmission capacity on the AT-IT border is allocated according to the day-ahead coordinated net transmission capacity based allocation approach; as explained in section 2.1.4, the transmission capacity on the FR-DE border, allocated according to the flow-based capacity allocation approach[10], are modelled using cross-border physical flows.

2.2 Temporal data

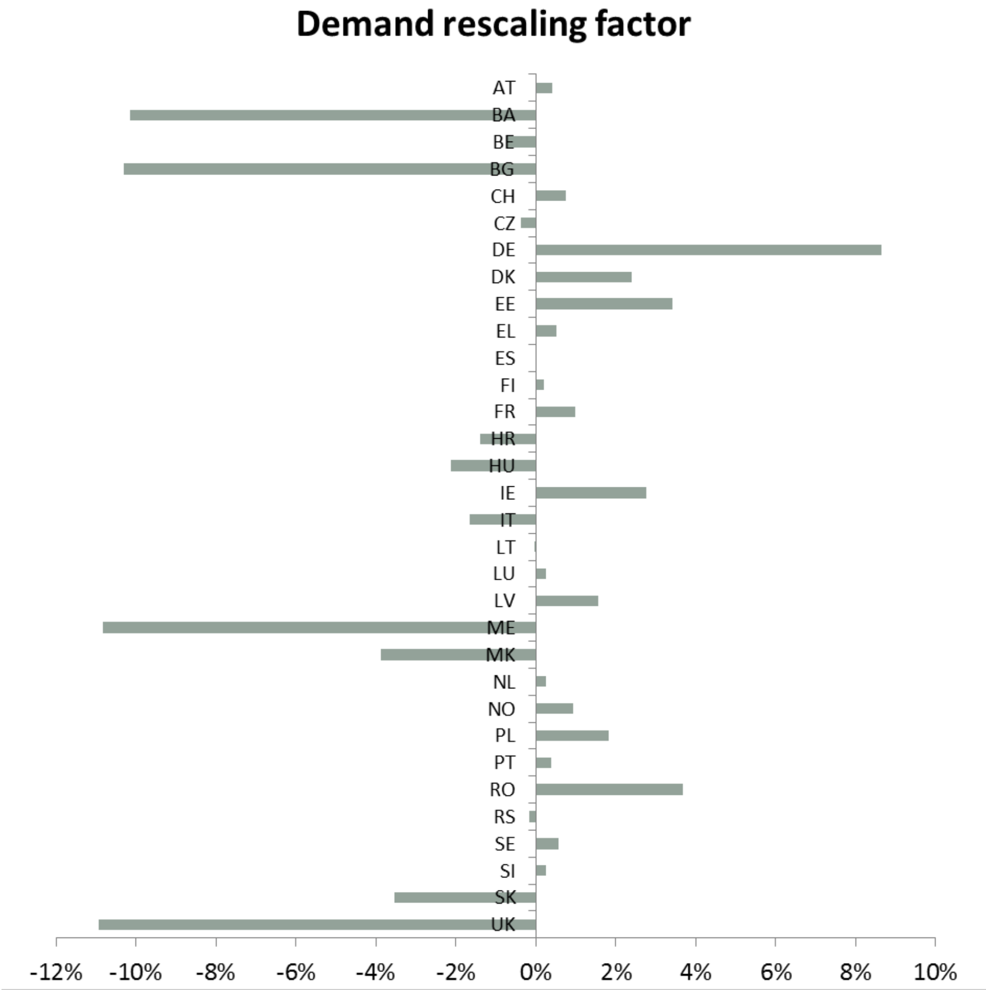
The temporal dataset contains input which is time dependent. Such data typically include demand, resource and technical availability and water inflows (for Hydro). In the current context these were extended to commodity (fuels and CO_2) prices and technical availability of NTCs.

2.2.1 Power demand

The historical hourly total demand time-series from ENTSO-E power statistics[11] for 2016 were used as the starting point for developing the current context. During the first calibration phase discrepancies in the data were discovered when compared with annual statistical demand data from EUROSTAT and national sources. The reason for the discrepancies could be due to the inclusion or not of own use in power plants and transmission and distribution losses, and the fact that some member states have islands which are not part of the ENTSO-E area (e.g. Spain and Greece).
Re-scaling was applied to the time series in order to match the annual energy with the (annual) values reported by ENTSO-E on their statistical factsheet for 2016[12] (see Figure 5).

[10] Commission Regulation (EU) No 543/2013, Art. 11.1
[11] https://www.entsoe.eu/data/power-stats/hourly_load/
[12] https://docstore.entsoe.eu/Documents/Publications/Statistics/Factsheet/entsoe_sfs_2016_web.pdf

Figure 5 Rescaling factor applied to demand time series



The METIS 2016 current context includes a database of temperature corrected synthetic demand time series developed in the context of the EMHIRES JRC project. The synthetic demand is based on historical 2015 actual load time series provided by ENTSO-E, corrected with 30 years (1986-2015) of hourly temperature time series at NUTS-2 from NASA (MERRA-2). The approach followed is summarised below:

- country-level hourly temperature time series have been obtained from NUTS-2 hourly time series through population-based weighting;
- from 2015 power demand time series and 2015 temperature time series, a regression analysis has been carried out to identify suitable statistical parameters for temperature correction
- 2015 power demand time series have been therefore corrected for exploiting the regression parameters and the country-based temperature time series for different climatic years.

2.2.2 Hydro inflows and reservoirs

Hydrological inflows affect significantly the results of the simulation of a power system. Energy that is generated from run-of-river and dams is subject to the availability of physical resources. In the current context inflow time series and hydro reservoir capacities based on reconciliation work combining data from ENTSOE and various TSOs were used[13]. In Annex 3 we compare the inflows time series with other sources found in literature and which could be considered for potential improvements in the future.

[13]https://ec.europa.eu/energy/sites/ener/files/documents/metis_technical_note_t1__integration_of_primes_scenarios_into_metis.pdf

Table 7 Annual Inflows and reservoirs in the current context before adjustments

Country	Annual inflows (TWh/year)	Reservoir capacity (GWh)
AT	12.32	3,668
BE	0	
BG	4.08	1,104
CZ	1.06	401
DE	2.04	408
ES	23.37	20,633
FI	7.12	4,748
FR	29.19	4,029
UK	5.12	
GR	4.97	3,347
HR	3.19	956
IE	0.66	301
IT	22.03	8,858
NL	0.11	46
PL	0.41	35
PT	6.81	5,960
RO	6.99	638
SE	70.22	32,090
SI	4.46	1,856
SK	4.09	408
BA	3.22	1,702
CH	20.33	8,820
ME	1.37	805
MK	1.47	625
NO	130.75	82,224
RS	0.75	119

Table 8. Rescaling applied to water inflows

Country	SF 2016	Initial run	Rescale factor
AT	10.2	10.7	0.95
BA	5.5	3.2	1.71
BG	2.2	4.1	0.54
CH	25.8	20.3	1.27
CZ	1.3	1.1	1.22
DE	0.6	2.1	0.29
ES	27.7	21.9	1.26
FR	26.8	31.1	0.86
GR	4.8	5.0	0.96
HR	4.3	3.3	1.30
IT	10.3	16.1	0.64
ME	1.4	1.4	1.02
NO	143.4	133.0	1.08
PL	0.7	0.4	1.83
PT	5.9	5.7	1.04
RO	7.9	7.0	1.13
RS	1.1	0.8	1.46
SE	61.2	70.2	0.87
SK	0.9	0.8	1.16

The water inflow time series presented in Table 7 were rescaled according to the values in Table 8, based on the initial modelling results related to power generation from hydro plants in order to match the annual generation reported by ENTSO-E on the Statistical Factsheet 2016.

2.2.3 Renewable generation

Wind solar and hydro run-of-river generation is an input to the model. Hourly generation time series based on historical and synthetic for 30 climatic years are used. As this study focused on benchmarking the model against the actual operation of the power system in 2016, the actual generation for wind and solar published in the ENTSO-E transparency platform, was adjusted in order to align with the published ENTSO-E statistical factsheet annual generation. The time series were predominantly consistent with the annual production figures. Rescaling factors were applied to the following four cases were significant deviation was observed.

Table 9. Rescaling applied to renewable generation time series

Country	Type	Rescaling
AT	Run-of-river	0.88
IT	Solar	1.25
LT	Solar	1.2
RO	Solar	1.22

2.2.4 Reserve requirements

Table 10 shows the values used to model reserve requirements for *Frequency Containment Reserve* (FCR), *automatic Frequency Restoration Reserve* (aFRR) and *manual Frequency Restoration Reserve* (mFRR). To fill them, the sources listed below have been used in the following order:

— accepted offers for reserves "up" and "down" from ENTSO-E Transparency Platform (95-th percentile value of the time series);

— National TSO figures;

— SEDC study "Explicit Demand Response in Europe – Mapping the Markets 2017";

— COWI 2015 study;

— outputs from the METIS reserve sizing algorithm

Looking at the values, it can be noted how the ENTSO-E Transparency Platform does not always provide sufficient information to identify the reserve requirements at European level. This could be related to the fact that the implementation process of Reg. (EU) 2017/2195 establishing a guideline on electricity balancing is still and ongoing process. Moreover, reserve definitions are still based on national grid codes, not necessarily matching the European Regulation ones.

The sum of FCR and aFRR is considered in METIS as synchronised reserve. Given the lack of completeness of the available information MFRR was not considered in this analysis of the current European System.

Table 10. Requirements for Frequency Containment Reserve (FCR), automatic Frequency Restoration Reserve (aFFR), manual Frequency Restoration Reserve (mFFR). All values are expressed in MW

Conutry	**FCR up**	**FCR down**	**aFRR up**	**aFRR down**	**mFRR up**	**mFRR down**	**Sources**
AT	67	67	271	375	284	173	SEDC[14], ENTSO-E TP
BA	14	14	135	97	NA	NA	METIS 2015, 2020
BE	68	68	144	144	780	780	Elia[15], ENTSO-E TP
BG	44	44	194	147	NA	NA	METIS 2015,2020
CH	68	68	391	388	NA	NA	Swissgrid[16], ENTSO-E TP
CY	NA	NA	NA	NA	NA	NA	
CZ	80	0	411	0	830	170	ENTSO-E TP
DE & LU	604	604	1,920	1,846	1,506	2,048	ENTSO-E TP
DK	54	47	190	190	NA	NA	ENTSO-E TP, COWI 2015
EE	45	45	NA	NA	549	433	METIS 2030, ENTSO-E TP
ES	421	421	2,240	1,405	1,713	1,527	METIS 2020, ENTSO-E TP, REE
FI	104	104	35	0	2,283	604	ENTSO-E TP
FR	847	847	923	752	11,957	4,187	ENTSO-E TP
UK	2,506	1,604	661	514	9,572	911	ENTSO-E TP, 2015 METIS
EL	60	60	248	198	NA	NA	COWI 2015, 2015 METIS
HR	10	10	149	109	NA	NA	COWI 2015, 2015 METIS
HU	104	104	572	562	NA	NA	ENTSO-E TP
IE	50	50	191	156	NA	NA	SEDC, 2015 METIS,
IT	535	535	650	462	4,060	4,060	METIS 2020, 2015 METIS,
LT	57	57	NA	NA	1,485	773	METIS 2030, ENTSO-E TP
LV	42	42	NA	NA	760	732	METIS 2030, ENTSO-E TP
ME	25	25	21	21	50	60	METIS 2020, ENTSO-E TP
MK	9	9	117	90	NA	NA	METIS 2015-2020
MT	NA	NA	NA	NA	NA	NA	
NL	95	95	543	752	115	120	ENTSO-E TP
NO	500	443	110	115	11,558	8,635	ENTSO-E TP
PL	176	176	569	563	NA	NA	ENTSO-E TP
PT	51	51	398	169	10,181	5,899	COWI 2015, ENTSO-E TP
RO	57	57	279	266	2,741	2,902	ENTSO-E TP
RS	46	46	235	175	3,205	2,536	METIS (2020, 2015), ENTSO-E
SE	780	780	445	336	4,301	4,339	ENTSO-E TP, METIS 2015
SI	10	10	61	61	348	185	COWI 2015, ENTSO-E TP
SK	32	32	156	141	644	412	ENTSO-E TP

2.2.5 Power plant availability

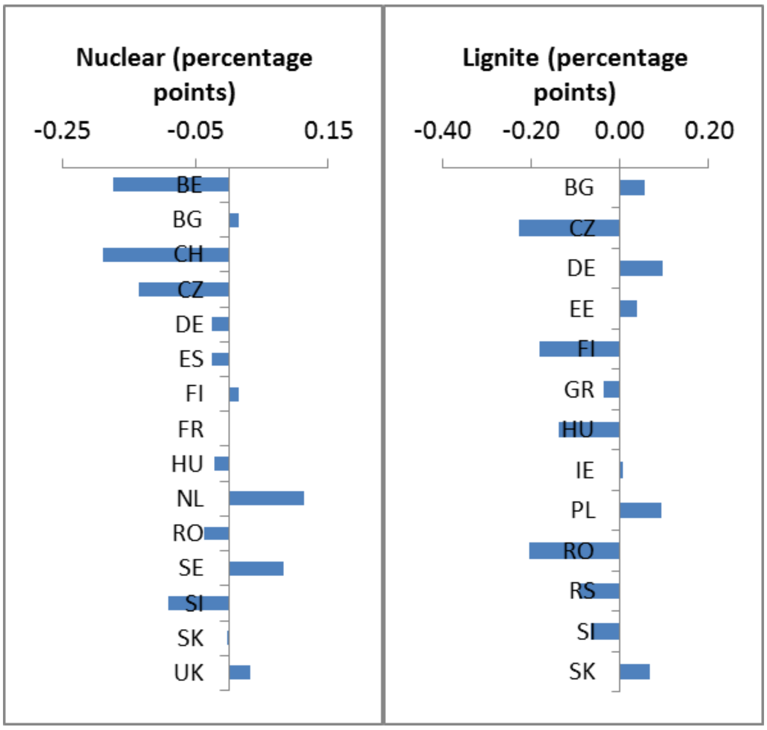
The default availability time series for the hard coal, lignite and nuclear fleets were updated during the calibration with year specific availability generated from outage reporting on the transparency platform.

Fossil and nuclear fleet availabilities have been validated in several sequential steps. The actual availability time series of the coal, lignite and nuclear fleets during 2016 were calculated based on the information on power plant outages (planned and forced) of generation units published by ENTSO-E on the Transparency Platform, which has been processed into a yearly time series of unavailable capacity per fleet per country. Based on this time series and under the assumptions that capacities without outages are available for generation an availability time series per fleet and country has been derived through division by the corresponding installed capacities in METIS based on ENTSO-E data.

[14] http://www.smarten.eu/wp-content/uploads/2017/04/SEDC-Explicit-Demand-Response-in-Europe-Mapping-the-Markets-2017.pdf
[15] http://www.elia.be/~/media/files/Elia/Products-and-services/ancillary%20services/purchase%20of%20ancillary%20services/EliaBy_Special_Ancillary%20Services_20170523_ENG_LR.pdf
[16] https://www.swissgrid.ch/dam/swissgrid/customers/topics/ancillary-services/as-documents/D170214-AS-Products-V9R2-en.pdf

Figure 6 compares for each fleet the average yearly availabilities between the ENTSO-E based time series and the METIS default time series, yielding the difference in percentage points between ENTSO-E and METIS. The actual numbers are provided in Annex 4.

Figure 6. Difference of yearly average availabilities (percentage points) between ENTSO-E outages (planned and forced) and METIS default time series[17]



Nuclear[18] and lignite fleet availabilities based on ENTSO-E transparency platform outage data vary significantly between countries. For these technologies the country specific actual availabilities were used. For the remaining technologies the default METIS values (Annex 4) were used. In the course of the analysis availabilities with hourly resolution have been inspected visually through plotting on charts and the ENTSO-E data has been used to update the METIS values where this led to more realistic dispatch behaviour of the fleets (both in terms of hourly and aggregate yearly generation). As a further step of fine-tuning the resulting availability time series were cross-validated with actual generation data for the corresponding fleets and where inconsistencies occurred (i.e. actual generation was higher than the computed availability) the availability was adjusted accordingly.

2.2.6 Fuel prices

The "contract" data in METIS refer to the price of fuels (natural gas, oil, lignite, and coal) as well as CO_2 allowance costs. The following price time series have been considered for use in the current context (all Platts' symbols obtained from EMOS unless otherwise stated):

— Coal: CSEUR00, daily prices of steam coal with a heat content of 6000 calories per kilogram delivered at the Antwerp-Rotterdam-Amsterdam port area, cost-insurance-freight included, in USD/metric ton, from 03/01/2007 to 01/31/2018.

[17] Please note that for lignite and coal fleets METIS by default uses one availability time series per fleet and that not for all countries with installed capacities outage time series were available on the ENTSO-E transparency platform

[18] In the latest update of the current context outages reported by EDF were used. In 2016 the average availability of the French Nuclear fleet was 74%.

— Gas: the following symbols have been used for these countries:

— Spain: GAOCA00 (Spanish PVB in EUR/MWh from 01/10/2015 to 01/31/2018) and MGSPA00 (MIBGAS Spanish PVB day ahead traded price, in EUR/MWh, from 01/12/2016 to 31/01/2018).

— Netherlands: GTFUX00 (Dutch TTF EUR/Gj day ahead, from 06/01/2004 to 31/01/2018).

— UK: GNCUU00 (UK NBP day ahead in EUR/GJ, 11/12/2006-31/01/2018) and GNCUY10 (UK NBP 1 year, EUR/GJ, 11/12/2006-31/01/2018).

— LNG: AASXU00 (LNG Northwest Europe marker, USD/BTU, 28/06/2010-31/01/2018) and AASXY00 (LNG Southwest Europe marker, USD/BTU, 28/06/2010-31/01/2018).

— Germany: AAJTX00 (German Bunde day ahead EUR/MWh, 02/09/2002-31/07/2009), GBBTD00 (German GASPOOL day ahead EUR/MWh, 18/06/2007-31/01/2018), and GERTD00 (NetConnect Germany day ahead EUR/MWh, 18/06/2007-31/01/2018).

— Belgium: AALKK00 (Zeebrugge day ahead price EUR/MWh, 01/04/2003-31/01/2018)

— France: GPGUD00 (France PEG day ahead, EUR/GJ, 18/06/2007-31/01/2018), AAPNP00 (Powernext PEG Nord day ahead, EUR/MWh, 06/07/2009-01/02/2018), and GPSTD00 (PED Sud/TRS day ahead, EUR/MWh, 06/04/2010-31/01/2018)/

— Nord Pool: GNPTD00 (Nord Pool gas day ahead, EUR/MWh, 16/05/2008-31/01/2018).

— Austria: GABTD00 (Austrian CEGH VTP day ahead, EUR/MWh, 01/12/2009-31/01/2018).

— Italy: GPVTD00 (Italian PSV day ahead, EUR/MWh, 18/06/2007-31/01/2018).

— Fuel: AAQCG00 (fuel oil with maximum sulphur content of 1% delivered in Rotterdam port area, free on board, loaded into barges in tonnes, EUR/metric ton, 14/02/2005-31/01/2018).

— Biomass: WPCT035 (wood pellet industrial cost CIF Northwest Europe, adjusted 35% efficiency, EUR/MWh, 15/08/2014-09/12/2016).

— CO_2: EADLP00 (EEX EUA CO_2e nearest December (Platts OTC until 28 April 2017), EUR/metric ton, 03/12/2012-31/01/2018).

— Uranium: Uranium, NUEXCO, Restricted Price, Nuexco exchange spot, US$ per pound (from IMF http://www.imf.org/external/np/res/commod/External_Data.xls), and ESA average natural uranium prices (2009-2015) (source: OECD-NEA Uranium 2016: Resources, Production and Demand), assuming 180 MBTU/lb (from http://www.uranium.info/unit_conversion_table.php) and 3.412 MBTU/MWh).

— EUR-USD exchange rates: ECB reference exchange rate, US dollar/Euro, 2:15 pm (C.E.T.) (EXR.D.USD.EUR.SP00.A, http://sdw.ecb.europa.eu/quickview.do?SERIES_KEY=120.EXR.D.USD.EUR.SP00.A).

The coal price based on the Thermal Coal CIF ARA index does not include the transportation costs to the plant site. We used the average reported price for steam coal for electricity generation by IEA[19] for Germany in 2016 to adjust the Coal CIF ARA index. This resulted in additional costs adding 17.5 EUR/ton to the Coal CIF ARA based price of coal. A flat 2 EUR/MWh surcharge was added to the gas price to account for transmission and other fees.

[19] IEA/OECD Energy Prices & Taxes

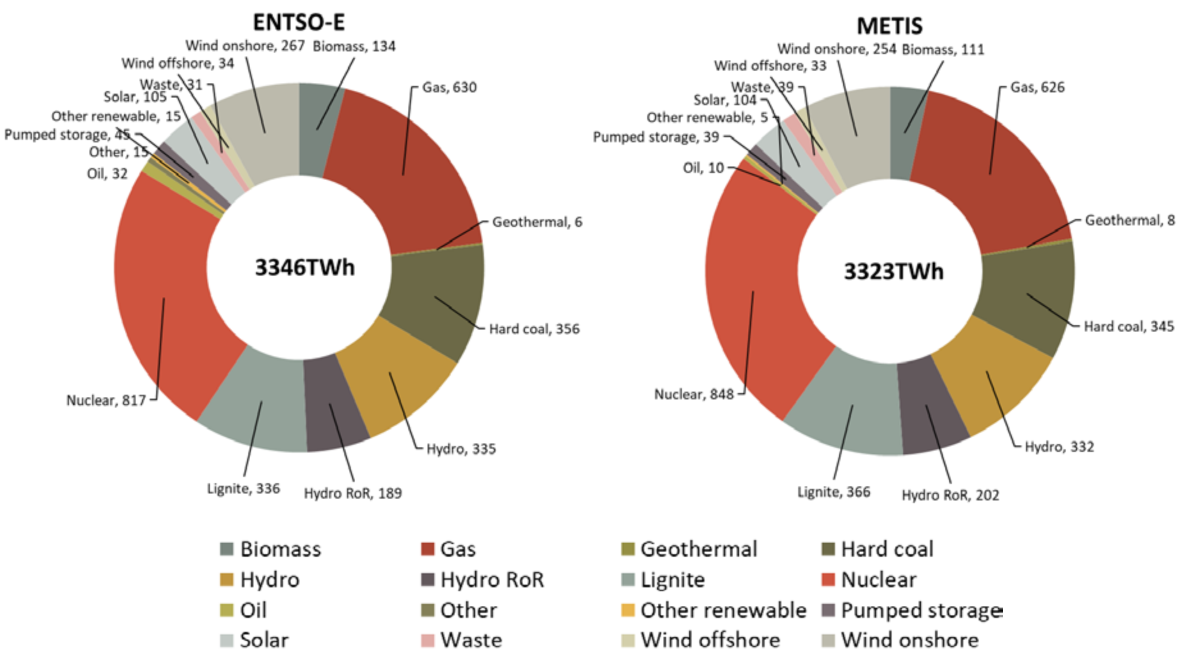
3 Simulation results

The calibration process involving all the above adjustments of the input presented in the previous paragraphs, took place in 6 different context iterations. The initial results based on synthetic demand and renewable generation time series based on the EMHIRES database showed reasonable ability to capture the annual fuel mix and it was then decided to proceed with a benchmarking versus the historical data. The results have come a long way in terms of representing the actual past operation of the power system. In Annex 5 the first results are provided in order to show the progress in calibrating the context with historical data. The following subsections present the data used and discuss the adjustments made in order to simulate more accurately the current European power system. In the subsequent paragraphs results of the last iteration are provided.

3.1 Annual generation mix

Figure 7 provides the contribution of each primary energy source in the annual generation for the modelled area, as reported by ENTSO-E[20], compared to the results of METIS.

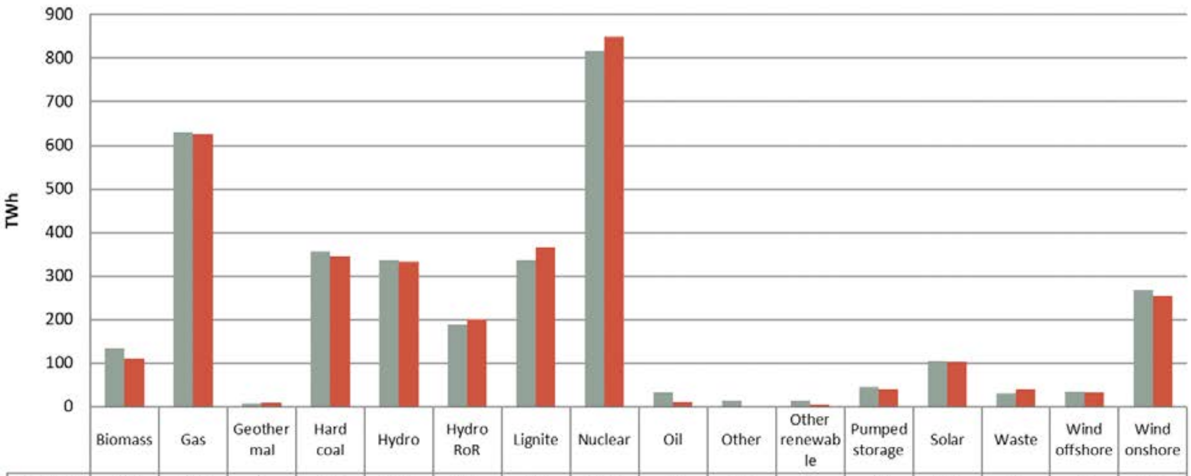
Figure 7 Energy mix ENTSO-E vs METIS results



Generation from the lignite and nuclear fleets is overestimated by approximately 10% and 3% respectively while gas consumption is underestimated by less than 1%. The difference can be attributed to the competitiveness of nuclear power and (to a lesser extent) lignite, compared to the other fossil fuels, in combination with the simplified representation of the gas-fired cogeneration fleets and transmission networks. Figure 8 in the following page provides a more direct comparison (modelled vs reported historical) in a bar chart. In Annex 6 a comparison of model results and actual fuel mix is provided for the EU28 member states.

[20] https://docstore.entsoe.eu/Documents/Publications/Statistics/Factsheet/entsoe_sfs_2016_web.pdf

Figure 8 Energy mix ENTSO-E vs METIS results



	Biomass	Gas	Geothermal	Hard coal	Hydro	Hydro RoR	Lignite	Nuclear	Oil	Other	Other renewable	Pumped storage	Solar	Waste	Wind offshore	Wind onshore
ENTSO-E	134	630	6	356	335	189	336	817	32	15	15	45	105	31	34	267
METIS	111	626	8	345	332	202	366	848	10		5	39	104	39	33	254

3.2 CO_2 emissions

The total CO_2 emissions modelled with METIS sum up to 980 million tons for the EU28. They are 2% lower than the actual 2016 emissions reported through E-PRTR by combustion facilities in power generation[21]. The total reported emissions by facilities rated higher than 50 MW_{th} for the modelled countries sums up to 1 000 million tons CO_2.
This deviation is consistent with the increased nuclear generation in the METIS simulation results, but not fully accounted by this (see Table 11).

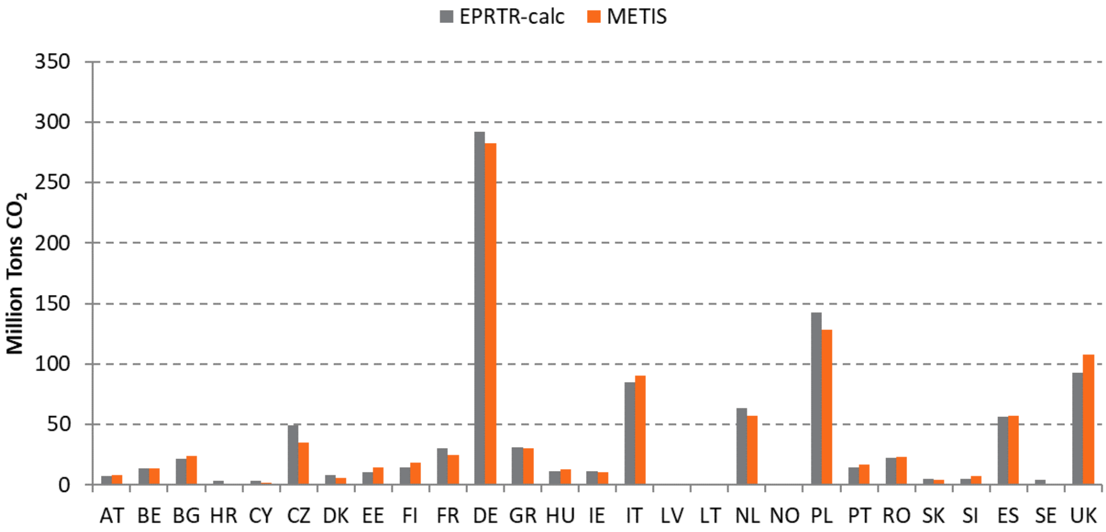
Table 11. Modelled vs actual fleet dispatching deviations and resulting emissions

Fuel	ΔTWh(e)	ΔCO_2(Mtns)
Gas	-4	-1.52
coal	-11	-10.6
Lignite	30	34.2
Oil	-22	-14.8
Total	-7	7.3

Accounting for the dispatching deviation among the CO_2–emitting technologies increases the gap to approximately 27 million tons (less than 3% of the total emissions). This can be attributed to CHP emissions being higher than currently modelled, as well as to E-PRTR reporting from industrial facilities. Figure 9 provides the country specific emission differences (historical vs modelled).
The most important deviations are present in countries with nuclear capacity (FR, SE, BE) and countries with significant industrial CHP facilities (CZ, DE, NL).

[21] E-PRTR database v.14 category "Thermal power stations and other combustion installations"

Figure 9 Reported emissions (E-PRTR) vs METIS results at country level

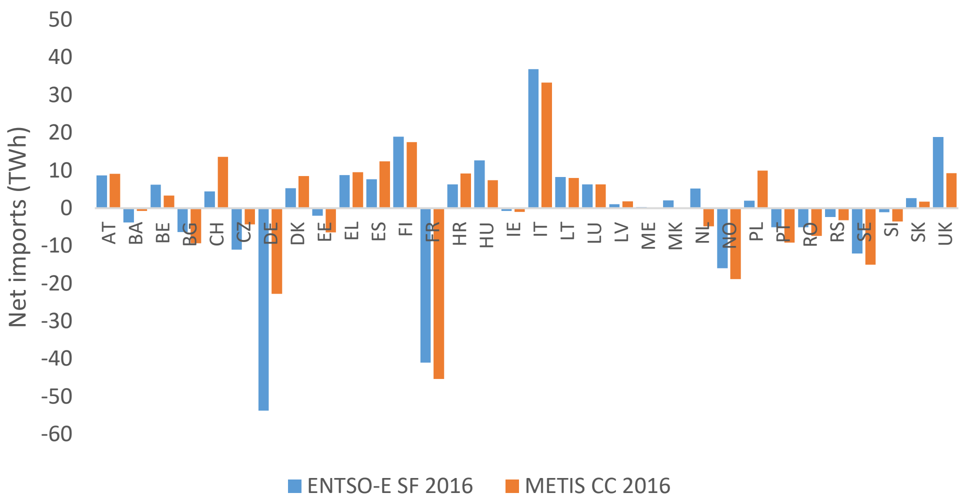


3.3 Net imports and congestions

Figure 10 shows the comparison of net imports at country level (import minus export) between the historical values provided by ENTSO-E, in 2016 Statistical Factsheet, and the results of the simulations carried out through METIS. It can be noted how, generally, METIS is able to catch the annual position of a country with respect to imports and exports, i.e. it is able to correctly identify if a country is a net exporter or a net importer. One notable exception is NL (importing 5.2 TWh according to ENTSO-E, exporting 4.6 TWh according to METIS).

In absolute numbers the highest deviation is registered in DE (53.7 TWh net export according to ENTSO-E, 22.7 TWh according to METIS). This difference is partially counterbalanced by an increase of net exports in FR (from 41.0 to 45 TWh) and a reduction of net import in UK (from 18.9 to 9.3 TWh). The reason behind these deviations has to be attributed to: i) the simplified representation of the generation system; ii) the cost-based rather than price-based dispatch strategy resulting by the minimisation of total variable costs; iii) limitations in the transmission network representation (physical behaviour of the transmission system is not represented) and iv) the CO_2 floor price in the UK not modelled in this iteration (see paragraph 3.4.1).

Figure 10 Comparison of net imports: ENTSO-E SF 2016 vs. METIS results at country level

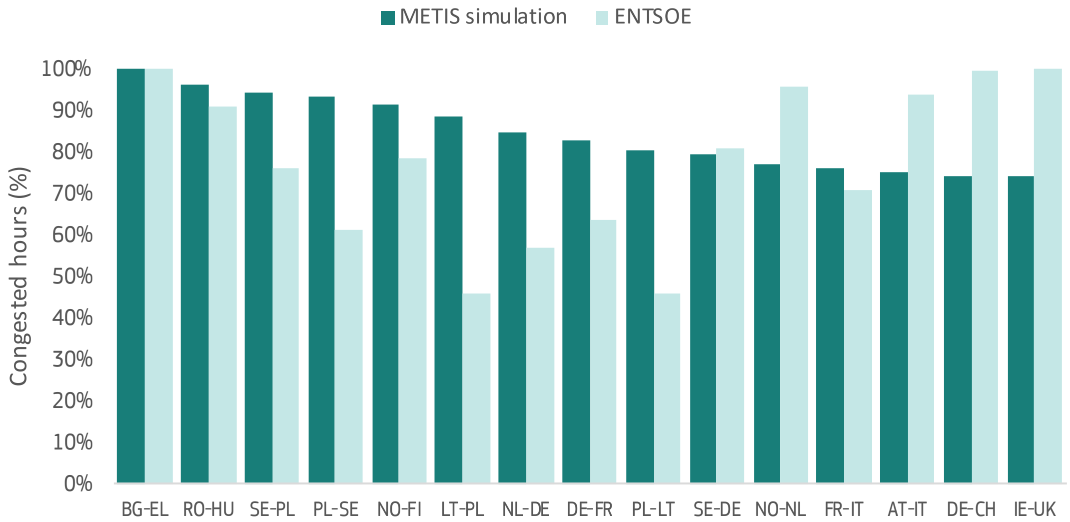


Annex 6 shows the full set of values for net imports in historical data from ENTSO-E Statistical Factsheet 2016 and METIS Current Context 2016 simulations.

Figure 11 shows the comparison of 2016 congestion hours (obtained from ENTSO-E Transparency platform) and the same quantity obtained from METIS simulations. An interconnection is defined "congested" in ENTSO-E Transparency Platform dataset if the price difference between the adjacent zones is greater than 0.01 EUR/MWh[22]. An interconnection is instead defined "congested" in METIS if the power flow through it is coincident with the maximum available capacity at the very time instant. Values are provided as a percentage of the reported hours for borders with incomplete annual records in the ENTSO-E Transparency Platform dataset.

Given the modelling limitation already pointed out, it can be noted how the comparison of congested hours between ENTSO-E and METIS values is of course coincident with the one on average price differences: congested hours for interconnection involving UK are lower in METIS than in ENTSO-E TP, while simulated congestion hours for interconnection involving the Baltic area are higher than historical values.

Figure 11 Congested hours: ENTSO-E TP 2016 vs. METIS CC 2016



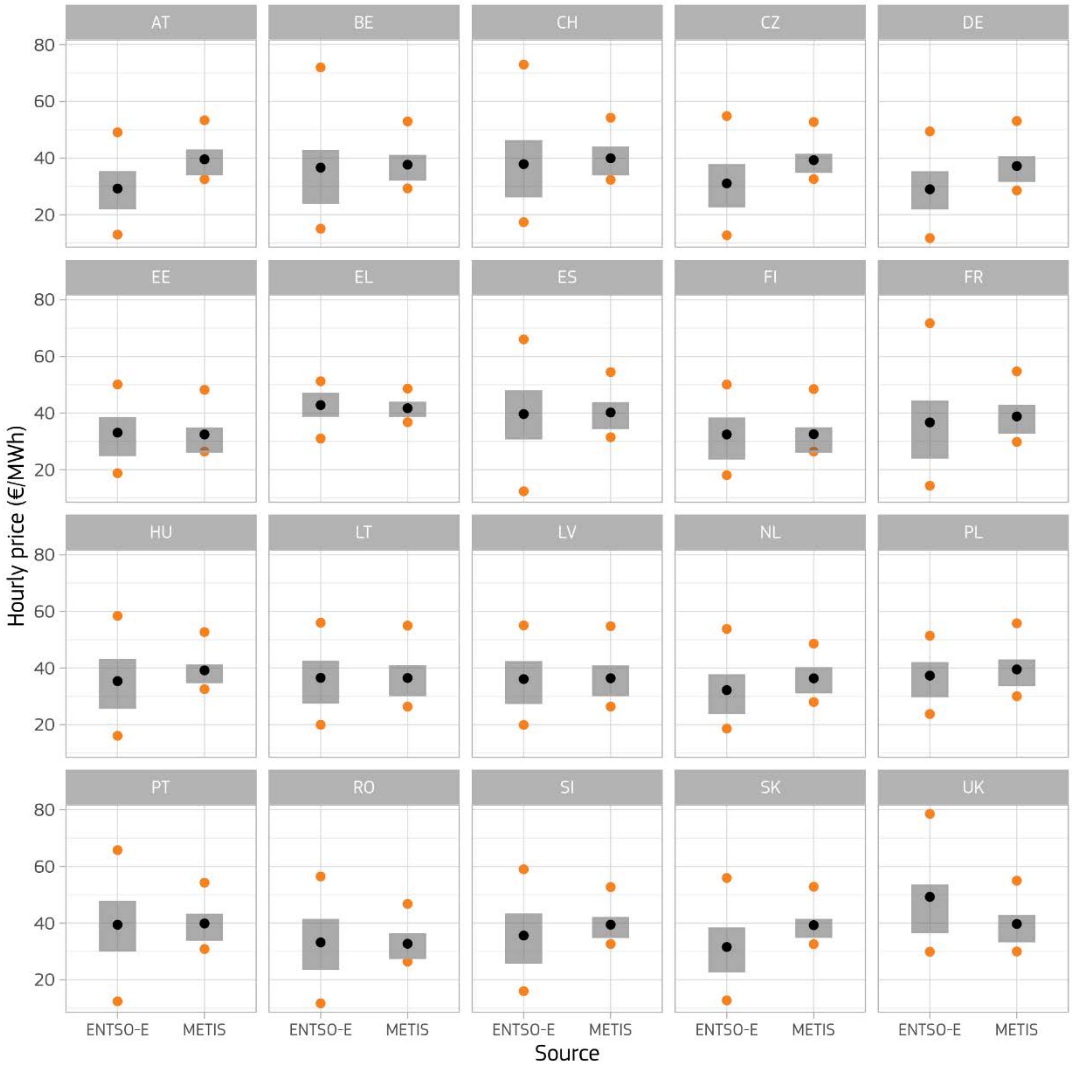
3.4 Power prices

Figure 12 shows the comparison of 2016 day head market prices (obtained from ENTSO-E Transparency platform) and the marginal prices obtained from the simulations with METIS: only values for countries where zones are geographically coherent between the observed and the simulated values are shown (i.e. there is no comparison for countries where bidding zones are not coincident with countries' borders like IT, NO and SE). The graphical comparison is performed showing, for each represented country, the 5th and the 95th percentiles (orange dots), the interquartile range 25th-75th percentiles (grey area) and the average (black dot) of hourly prices. Prices provided with a different time granularity (e.g. 15 min, 30 min) have been calculated as average values of resampled hourly values.

From a visual check, it can be noted how average values from ENTSO-E TP and METIS prices are generally close; in some countries (e.g. AT, CZ and SK) METIS is overestimating prices. It can be also pointed out how METIS prices show a smaller volatility with respect to historical values. This can be partially explained by the assumed fully competitive behaviour of bidding at the variable cost, but is also a signal that a more accurate representation of technical constraints should be considered.

[22] ENTSO-E day-ahead prices are approximated to EUR cents.

Figure 12 Boxplot day-ahead prices: ENTSO-E TP 2016 vs. METIS CC 2016. All the hourly prices greater than 500 €/MWh have been set to 500 €/MWh



We notice also that the 5[th] percentile price difference between METIS results and historical day-ahead prices is higher compared to the differences of the respective 95[th] percentile prices. By looking at the hourly price duration curves we can explain this and help to identify some patterns:

— Historical day-ahead prices (average and 95[th] percentile) are higher than the respective modelling results. This is spotted in the UK. Research into the possible reasons for this deviation revealed that the UK has implemented a carbon price support mechanism, which is essentially a floor price of CO_2 set at £18/tonne CO_2[23]. (see also Figure 13 for the price duration curves). The impact of this mechanism was presented in see paragraph 3.4.1.

— Historical day-ahead prices (average and 5[th] percentile) are lower than the respective modelling results. In these countries ENTSO-E day ahead prices assumed negative values (see for example Figure 14 for German prices), thereby deviating significant from the variable cost assumption used in dispatching models.

[23] https://www.ofgem.gov.uk/system/files/docs/2017/10/state_of_the_market_report_2017_web_1.pdf

Figure 13: Price duration curve for the United Kingdom (UK). All the hourly prices greater than 500 €/MWh have been set to 500 €/MWh.

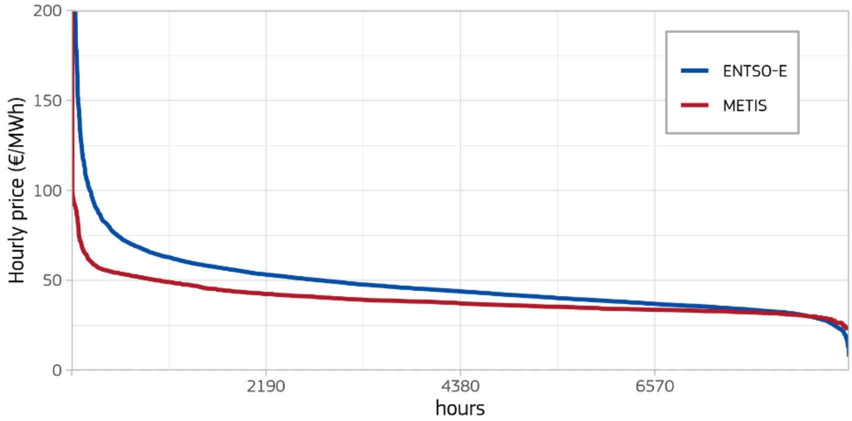


Figure 14: Price duration curve for Germany (DE)

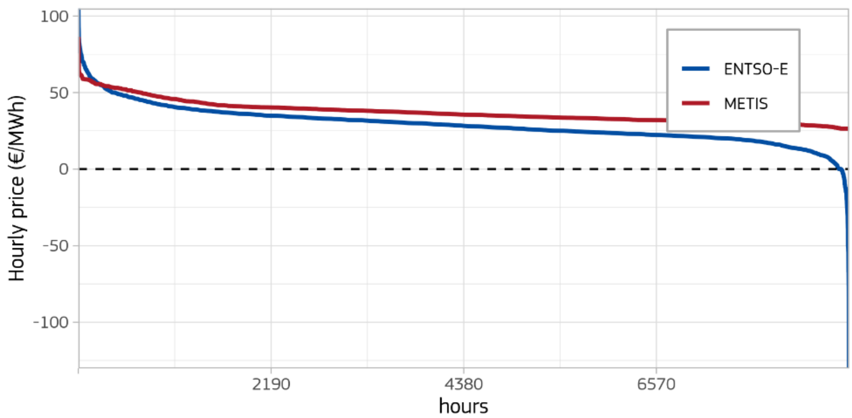


Figure 15: Price duration curve for France (FR)

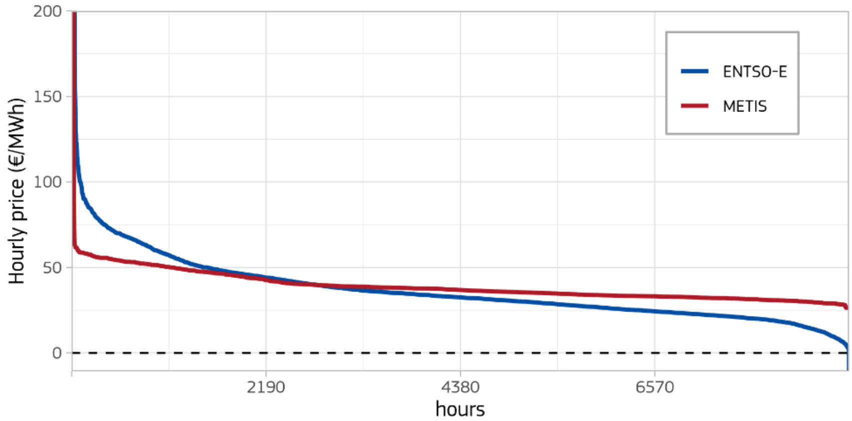


Table 12 provides a comparison of average absolute values of the price differential at borders with more than 8 000 annual records in ENTSO-E Transparency Platform and its comparison with hourly METIS values (obtained from ENTSO-E Transparency platform) and the marginal prices obtained from METIS simulations: for some borders (e.g. the ones involving UK) the average absolute value of price differential in METIS are lower than the corresponding historical ones, while in other cases (e.g. CH-FR and especially EE-FI) METIS is overestimating price differences..

Table 12. Comparison of average absolute values of price differences among borders with more than 8 000 annual records in ENTSO-E TP 2016

Border	ENTSO-E TP 2016	METIS CC 2016
UK - NL	17.86	11.07
FR - UK	17.76	9.84
UK - IE	13.85	9.90
ES - FR	7.97	3.17
BE - NL	6.05	2.15
CH - FR	4.94	2.24
HU - SK	3.87	0.38
EE - LV	3.10	3.96
HU - RO	2.70	6.53
BE - FR	2.53	1.22
EE - FI	0.73	0.21
LT - LV	0.45	0.08
CZ - SK	0.45	0.03
ES - PT	0.34	0.35

3.4.1 The carbon price support mechanism in the UK

A sensitivity analysis of the current context was performed to analyse the effect of the price support mechanism in the UK. The resulting price duration curve (green) illustrates that failing to consider the carbon price floor results in a biased underestimation of the marginal price, which for 2016, is significant. The modelling results show a price impact higher than 7€/MWh (see Table 13 and Figure 16) and a price convergence with actual day-ahead prices.

Figure 16 Simulated day-ahead marginal price duration curve with (N) and without (M) a cO2 price floor vs actual day-ahead market prices

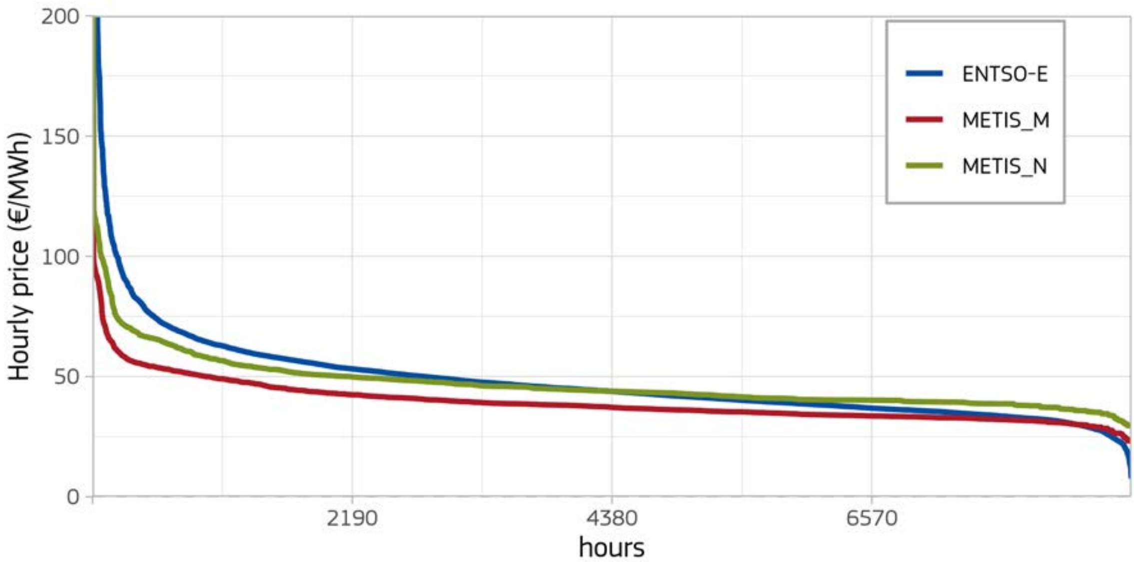


Table 13. Average price excluding outliers above 500€/MWh

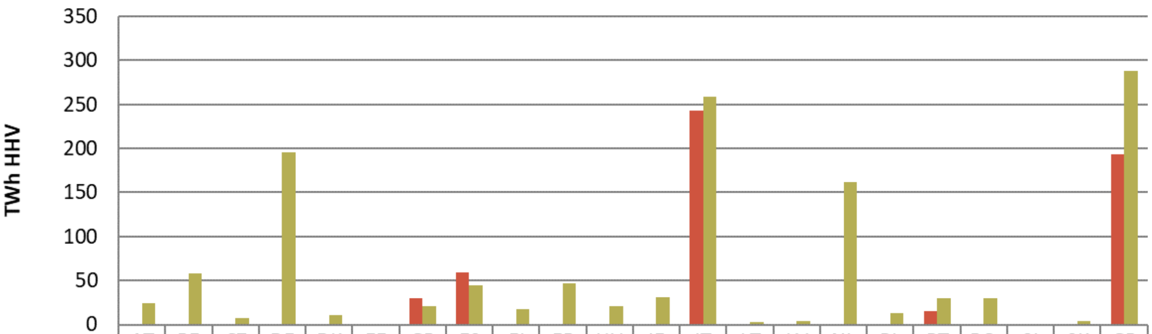
Source	CO_2 modelled price	Average price
ENTSO-E	-	48.3
METIS_M	EU ETS CO_2 price	39.3
METIS_N	18 £/tonne CO_2	46.7

However, the modelled dispatching involved significantly more fuel switching (from coal to gas), therefore diverging from the actual fleet operation. This result signals that the short run marginal cost was not the only criterion for dispatching the UK coal fleet on 2016. This is an area were subsequent analysis will look deeper into.

3.5 Gas consumption

The total simulated gas consumption in the modelled area calculated in the current context for 2016 is 1156 TWh HHV. The graph below provides the country gas consumption by power plants benchmarked against published demand for power generation in 5 selected countries.

Figure 17 Simulated annual gas consumption



	AT	BE	CZ	DE	DK	EE	GR	ES	FI	FR	HU	IE	IT	LT	LV	NL	PL	PT	RO	SI	SK	GB
Gas TSO							29.4	59.6					243					15.4				193
METIS	25	58	8	196	11	0	21	44	18	47	21	32	258	3	4	162	13	30	30	1	4	288

The benchmarking of gas demand against historical values is not straightforward since published reliable information is not available for every country and there is a big uncertainty on derived data. A few gas TSOs publish aggregate gas demand by power generation or flows at specific gas system exit points serving power plants. However even in these cases it is possible that gas demand for power generation at the distribution level is not accounted for.

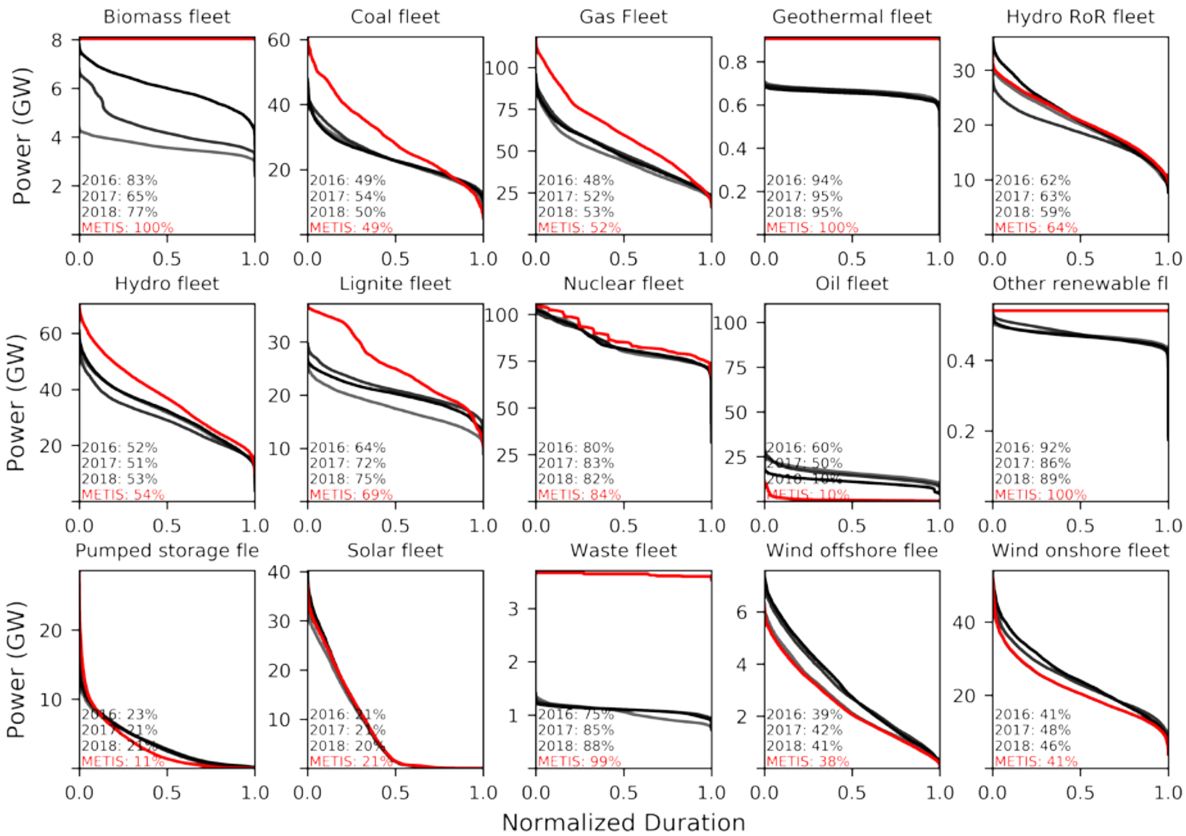
3.6 Temporal results comparison

Observing the load duration curves of the historical European power generation compared to the simulation results can give some insight on the accuracy of the simulation results. A load duration curve corresponds to the generation which is sorted from the highest to the lowest value for one specific year. These curves describe the peakiness (slope), maximum power (maximum value in y-axis) and the amount of energy generated (area under curve). A limitation of the load duration curve comparison method is that the load coincidence is not observed; the peak simulated may not occur at the same time with the historical. Nevertheless it gives a very good overview of the main statistical features of the time series.

The historical load duration curves are created from ENTSO-E transparency platform (*AggregatedGenerationPerType*). Figure 18 shows three years (2016, 2017, and 2018) of historical power generation in Europe grouped by energy generation technologies for the 30 countries that exist on both METIS and ENTSO-E datasets[24]. A detailed country by country view is presented in Annex 10.

[24] For the following countries: BA, CH, EE, PT, NL, IT, FR, LV, UK, CZ, MK, RO, RS, EL, FI, BE, PL, SI, CY, DK, IE, SK, HU, SE, BG, AT, ME, LT, NO, and ES.

Figure 18. Power plant generation per technology in the form of load duration curves.



Simulation results are shown in red. Historical Load Duration curves per technology for EU countries for 2016–2018. The darker line corresponds to 2018. The annotated percentages correspond to the capacity factor of each technology/year.

The simulation results show very good coincidence with the observed historical data. Technology-based observations are summarized below:

— Biomass and geothermal fleet: they are modelled as must-run, which explains their flat load duration curve.

— Coal and gas fleet: capacity factors show very good coincidence with historical. Simulated peak seems to be higher than historical but this is due to the fact that smaller units may be missing from transparency platform dataset.

— Hydro units (storage, run of river and pumped storage): capacity factors show very good coincidence with historical data in most countries. Available capacities were fine-tuned considering also the cascade effects.

— Nuclear fleet: the shape of curve is very dependent on planned outages, simulations slightly overestimate the amount of nuclear generation. As explained later this is related to the French nuclear fleet.

— Wind and solar: as expected, they present almost a perfect match as they follow closely the input availability factors.

— Oil fleet: the energy generation is lower than the historical, this is probably due to input oil prices and installed capacity.

In Annex 8 a comparison of the fleet dispatching during 96 consecutive hours during winter and summer is provided for the EU28 member states. Country and technology specific differences are presented in Annex 10.

3.7 Weather Impact on the current power system

In the preceding paragraphs the current context based on the European power system was modelled and the results were compared to the actual historical operation of the power systems. In this analysis the actual electricity demand as well as the actual wind and solar hourly generation were used. The current context was extended with the EMHIRES dataset which contains hourly wind and solar hourly generation relevant to an additional 30 climatic years (1986 – 2015) as well as a temperature corrected synthetic demand time series (see 2.2.1). This feature was used to conduct a first assessment of the impact of the climatic years on the total CO_2 emissions, as well as the variability of the average system marginal price.

The variability assessment presented below is induced by the wind, solar and demand variability in the 30 years examined. It therefore does not consider precipitation variability which affects hydro production. The 30 years climatic cases in METIS assume the identical power plant fleet characteristics, and commodity prices including availabilities. However the modelling of the interconnection availability is less constrained as 100% available interconnector capacity is considered. This may well be one important factor reducing the overall CO_2 emissions of the system compared to the base 2016 case.

3.7.1 Variability of CO2 emissions

The CO_2 emissions calculated by METIS in the current context are 980 million tonnes. The median value in the results of the 30 climatic years is somewhat lower (961 million tonnes) while the standard deviation is 20 million tonnes. Figure 19 provides further insight on the weather impact on emission variability. The interquartile range (25^{th}-75^{th} percentiles) is provided in the blue area.

Figure 19. Boxplot of CO_2 emissions in the 30 climatic years for the EU28

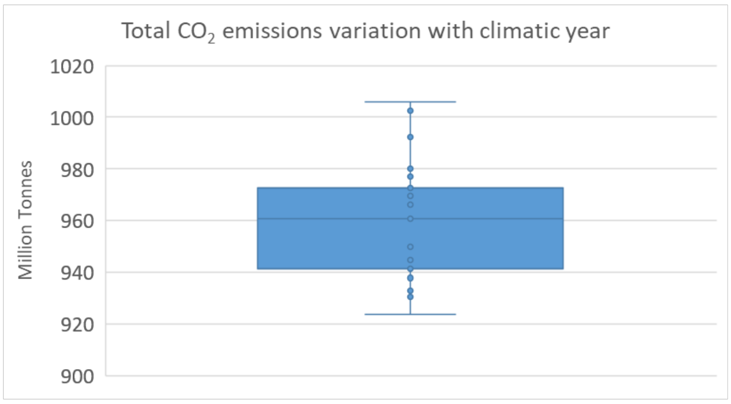
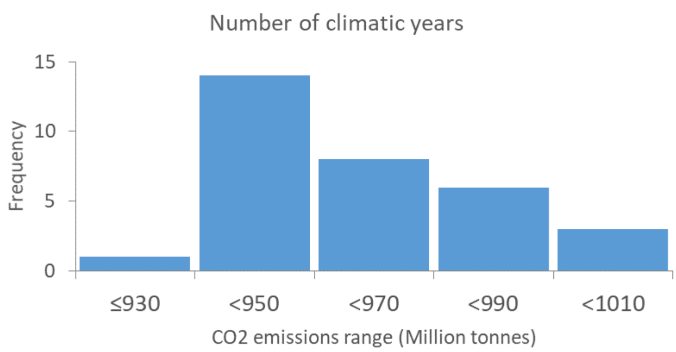


Figure 20. Histogram of the 30 climatic years with regard to EU28 CO_2 emissions



The weather-induced variability is significant and scenarios range from emissions below 930 million tonnes (1 year) to above 990 (3 years).

3.7.2 Variability of average marginal prices

The average marginal price variability induced by weather is more significant in the Nordic area and or countries with significant Nuclear capacity and propagates to well interconnected countries in Central Europe as Figure 21 illustrates. However further research is required in order to definitely assert the robustness of this finding.

Figure 21. Relative average price change in the 30 climatic years simulations

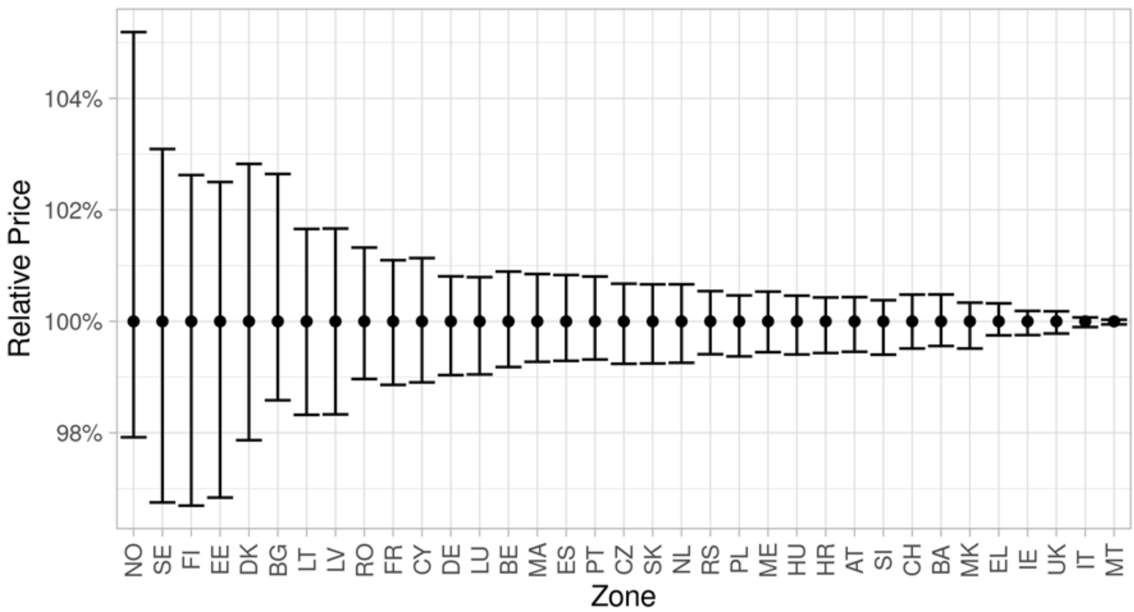
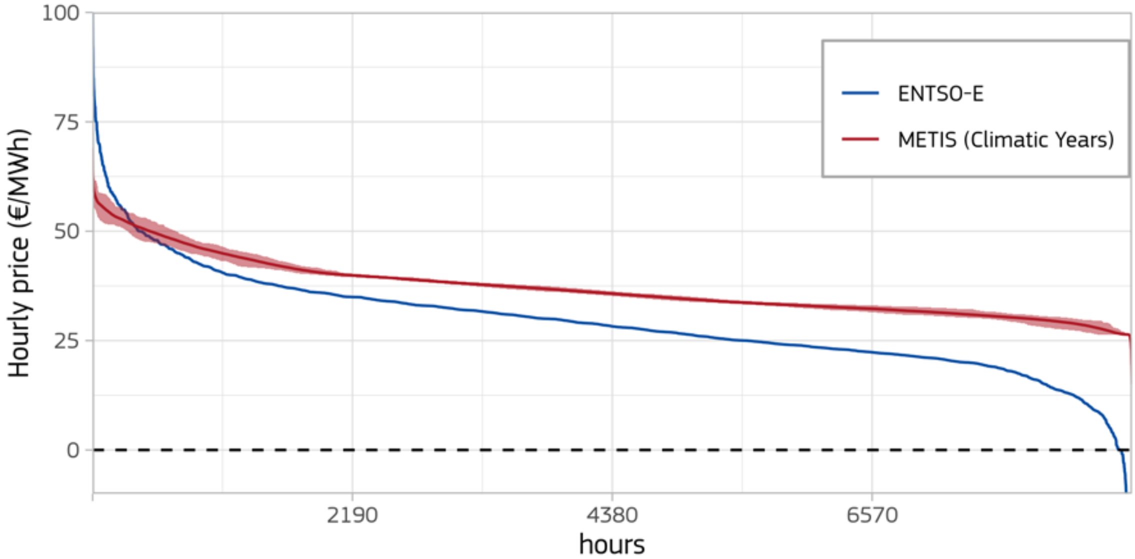


Figure 22. Climatic year effect on the price duration curve range



The effect of the climatic variability on the hourly marginal prices appears less significant than other assumptions (such as fuel cost or bidding behaviour modelling. An illustration of this is provided in Figure 22 for the German day ahead price. The results of the model suggest, rather intuitively that prices are more affected at the extremes (which correspond to peak and minimum load hours).

4 Conclusion and potential future work

The present report outlined the data and assumptions used, as well as the methodology applied, in order to simulate the operation of the current (as of 2016) European[25] power system with METIS. A significant amount of effort was dedicated to align with the actual (where available) published information for 2016. This allowed benchmarking with the actual operation of the power system.

4.1 Assessing the METIS current context

A first assessment of the context, based on the benchmarking process, may be summarized below:

- The model can capture well annual EU, and in most cases country aggregates (fuel mix and CO_2) emissions.
- The model underestimates aggregate CO_2 emissions by less than 3%. This bias can be further reduced by a better representation of the CHP fleet operation.
- Fleets which are marginal (i.e. gas in a mostly nuclear country like France or Sweden) produce somewhat more in reality than in the METIS simulation. In these countries CO_2 emissions are thus underestimated.
- At the temporal level, with the exception of must run fleets (biomass and waste) the simulation results show very good coincidence with the observed historical data.
- The marginal price calculated by METIS prices show a smaller volatility compared to historical values, which is expected due to the assumed fully competitive behaviour of bidding at the variable cost as well as the aggregated representation of capacity fleet in the modelling.
- Based on the real data (ENTSO-E) fuel switching from coal to gas occurred at a higher (case of UK with the carbon price support mechanism) or lower pace (case of ES) than historical commodity prices suggest (modelled results) in countries where coal competed with gas, suggesting that short term marginal cost is not the only driver behind power plant dispatching.

All of the above may be attributed, up to a certain extent, to the limitations of the model (variable cost based dispatching, coarse spatial representation, etc.) which fails to capture inter-sectoral synergies, local bottlenecks, bidding strategies, inadequate competition, contractual agreements such as take-or pay and much more.

4.2 Input data quality

However it is the authors' view that by far the most important factor affecting the results is the quality of the input. The data published today on the European (ENTSO-E, ENTSO-G, E-PRTR, etc.) provide a very good starting point for producing largely coherent results in our simulations of the operation of the European power system. We identified areas where input data quality is affecting the results and has significant room for improvement:

- The different sets of statistics published by ENTSO-E are not consistent among themselves and significant variations are found across the available statistics of each country.
- The available statistical sources (ENTSO-E, EUROSTAT, etc.) use different categorisations for the power generation technologies (e.g. hydro is split into technologies by ENTSO-E and by facility size by EUROSTAT).
- Reliable annual gas consumption data for power generation are still not available for most countries.
- Estimating accurately the fuel cost of thermal power plants is a challenge due to the very limited availability of data on fuel prices, particularly for indigenously extracted coal and lignite, but also for coal and gas where transportation and transmission costs are not readily available.
- There are very few sources of hydro-related data (reservoir capacity, storage levels, inflow data, etc.). The quality the different sources exhibit significant variability.

[25] EU28 and Norway, Switzerland, and the countries of the western Balkans

— The ENTSO-E Transparency Platform does not always provide sufficient information to identify the reserve requirements at European level.

4.3 Potential future work

The benchmarking of METIS results in the current context against 2016 historical data proved that the model can successfully estimate annual aggregated energy indicators (country fuel mix, CO_2 emissions), as well as the temporal operation of the generating fleets. The analysis of the results identified areas for potential further work:

1. Aiming to refine and improve the dataset and assumptions:
   (a) By further analysing the carbon price support mechanism in the UK and a case study on a possible extension to the rest of the EU.
   (b) By further refining the coal and gas cost assumptions across the EU.
   (c) By further refining the climatic dataset.
2. To further validate the model and solidify the conclusions by extending the analysis to more years.
3. to improve the model:
   (a) By introducing a new feature to simulate the bidding behaviour of generators.
   (b) By extending the analysis to an integrated of gas and electricity current context.

References

K. Kanellopoulos, I. Hidalgo, H. Medarac, A. Zucker, The Joint Research Centre Power Plant Database (JRC-PPDB) - A European Power Plant Database for energy modelling, EUR 28549 EN, doi:10.2760/329310

Kanellopoulos K., De Felice M., Hidalgo I., Bocin A., Uihlein A, The Joint Research Centre Power Plant Database (JRC-PPDB) – Version 0.9, EUR 29806 EN, Publications Office of the European Union, Luxembourg, 2019, ISBN 978-92-76-08849-3, doi:10.2760/5281

COWI, Ecofys, VITO and Thema (2016): Impact assessment study on downstream flexibility, price flexibility, demand response & smart metering.
https://ec.europa.eu/energy/sites/ener/files/documents/demand_response_ia_study_final_report_12-08-2016.pdf

EEA, European Pollutant Release and Transfer Register (E-PRTR), https://www.eea.europa.eu/data-and-maps/data/member-states-reporting-art-7-under-the-european-pollutant-release-and-transfer-register-e-prtr-regulation-21/european-pollutant-release-and-transfer-register-e-prtr-data-base

ENTSO-E power statistics: https://www.entsoe.eu/data/power-stats/

ENTSO-E Transparency Platform, https://transparency.entsoe.eu/.

ENTSO-E statistical factsheet, https://www.entsoe.eu/publications/statistics-and-data/#statistical-factsheet

EURELECTRIC-VGB Hydropower factsheets https://www.vgb.org/en/hydropower_fact_sheets_2018.html
F. Geth, T. Brijs, J. Kathan, J. Driesen, R. Belmans. An overview of large-scale stationary electricity storage plants in Europe: current status and new developments. Renew Sustain Energy Rev, 52

GONZALEZ APARICIO Iratxe; ZUCKER Andreas; CARERI Francesco; MONFORTI Fabio; HULD Thomas; BADGER Jake; EMHIRES dataset. Part I: Wind power generation European Meteorological derived High resolution RES generation time series for present and future scenarios; EUR 28171 EN; 10.2790/831549.

GONZALEZ-APARICIO Iratxe, HULD Thomas, CARERI Francesco, MONFORTI Fabio, ZUCKER Andreas; EMHIRES dataset - Part II: Solar power generation. European Meteorological derived HIgh resolution RES generation time series for present and future scenarios. Part II: PV generation using the PVGIS model; EUR 28629 EN; doi: 10.2760/044693

IRENA hydropower statistics, https://www.irena.org/hydropower

NASA, Modern-Era Retrospective analysis for Research and Applications, 2019, Version 2, https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/

Smart Energy Demand Coalition (SEDC). Explicit Demand Response in Europe. Mapping the Markets. 2017. https://www.smarten.eu/wp-content/uploads/2017/04/SEDC-Explicit-Demand-Response-in-Europe-Mapping-the-Markets-2017.pdf

List of abbreviations and definitions

CAPEX	Capital expenditure
CCGT	Combined cycle gas turbine
CHP	Combined heat and power
NTC	Net transfer capacity
OCGT	Open cycle gas turbine
OPEX	Operational expenditure
RoR	Run of River
VRE	Variable renewable energy

List of figures

List of tables

Annexes

Annex 1. Installed capacity of thermal and renewable fleets

Table 14. Installed capacity of thermal and renewable fleets in the current context

Country	Biomass	Coal	Gas	Lignite	Nuclear	Oil	Solar	Wind offshore	Wind onshore
AT	0.49	0.69	4.3				0.73		2.49
BA				1.88					
BE	0.92	0.47	5.79		5.92		3.09	0.71	1.58
BG	0.06	0.54	0.36	4.19	2		1.04		0.7
CH					3.37		0		0.12
CY	0					1.48	0.1		0.16
CZ	0.35	1.2	0.85	7.93	3.94		2.03		0.28
DE	6.81	28.2	24.11	20.1	10.8	1.14	40	3.28	41
DK	1.07	3.13	1.07			0.52	0.85	1.27	3.81
EE	0.08		0.17	2.25			0		0.38
ES	1.57	10.3	29.89		7.57		6.5		22.8
FI	1.53	3.34	1.8	0.97	2.78	0.76	0	0	1.08
FR	0.47	2.93	6.58		63.1	6.67	6.2	0	10.3
GB	1.89	14	37.27		8.98	0.99	9.06	5.01	9.2
GR	0.05		5.25	3.91			2.44		1.88
HR	0.03	0.34	1.45			0.36	0.05		0.49
HU	0.25		3.33	1.05	1.9	0.41	0.03		0.33
IE	0.15	0.86	5.02	0.23		1.2	0	0.03	2.74
IT	1.61	7.61	36.42			2.17	18.9		9.42
LT	0.07		1.52				0.07		0.51
LU	0.03						0.12		0.12
LV	0.07		1.03				0	0	0.07
ME				0.21					
MK	0.02		0.25	0.82			0		0.04
MT	0					0.73	0		
NL	0.4	4.67	19.9		0.49		1.43	0.36	3.28
NO			1.36						0.87
PL	0.74	20.1	1.57	8.92		0.42	0.11	0	5.49
PT	0.58	1.76	4.7				0.43		5.05
RO	0.1	1.33	3.46	3.78	1.3		1.23		2.94
RS			0.12	5.54		0.14	0		
SE	2.02		0.25		8.41	2.17	0	0	5.96
SI	0.06		0.3	0.92	0.7		0.26		0
SK	0.22	0.22	0.58	0.33	1.94		0.53		0

Annex 2. Rescaling of power demand applied to the 2016 time series

Table 15. Power demand from different sources and rescaling factor applied

Country	Annual demand [TWh]				Rescale factor
	ENTSO-E Power Statistics	Eurostat 2016	ENTSO-E SF 2016	AGORA	
AT	70.0	61.9	70.3	72	1.004
BA	13.7	11.1	12.3		0.899
BE	84.8	81.8	84.2	91	0.993
BG	37.6	28.9	33.7	38	0.897
CH	62.6	na	63.1		1.008
CZ	65.1	56.1	64.9	71	0.996
DE	504.7	517.4	548.4	593	1.087
DK	33.9	31.2	34.7	36	1.024
EE	8.1	7.3	8.4	10	1.034
ES	249.8	232.5	265.0	279	1.000
FI	84.8	80.8	85.0	88	1.002
FR	478.3	442.4	483.1	510	1.010
UK	375.0	303.9	334.0	354	0.891
EL	51.0	53.5	51.3	60	1.005
HR	17.5	15.3	17.3	18	0.986
HU	41.8	37.1	40.9	45	0.979
IE	26.9	25.6	27.6	29	1.028
IT	313.6	286.0	308.4	325	0.983
LT	11.4	9.8	11.4	12	1.000
LU	6.5	6.4	6.5	7	1.003
LV	7.2	6.5	7.3	7	1.016
ME	3.6	2.7	3.2		0.892
MK	7.4	6.2	7.1		0.961
NL	114.2	105.6	114.5	120	1.002
NO	132.0	113.6	133.2		1.009
PL	152.5	132.8	155.3	168	1.018
PT	49.1	46.4	49.3	54	1.004
RO	53.4	43.3	55.4	60	1.037
RS	38.9	27.3	38.8		0.998
SE	139.0	127.5	139.8	144	1.006
SI	13.8	13.0	13.8	15	1.002
SK	28.7	25.0	27.7	29	0.965

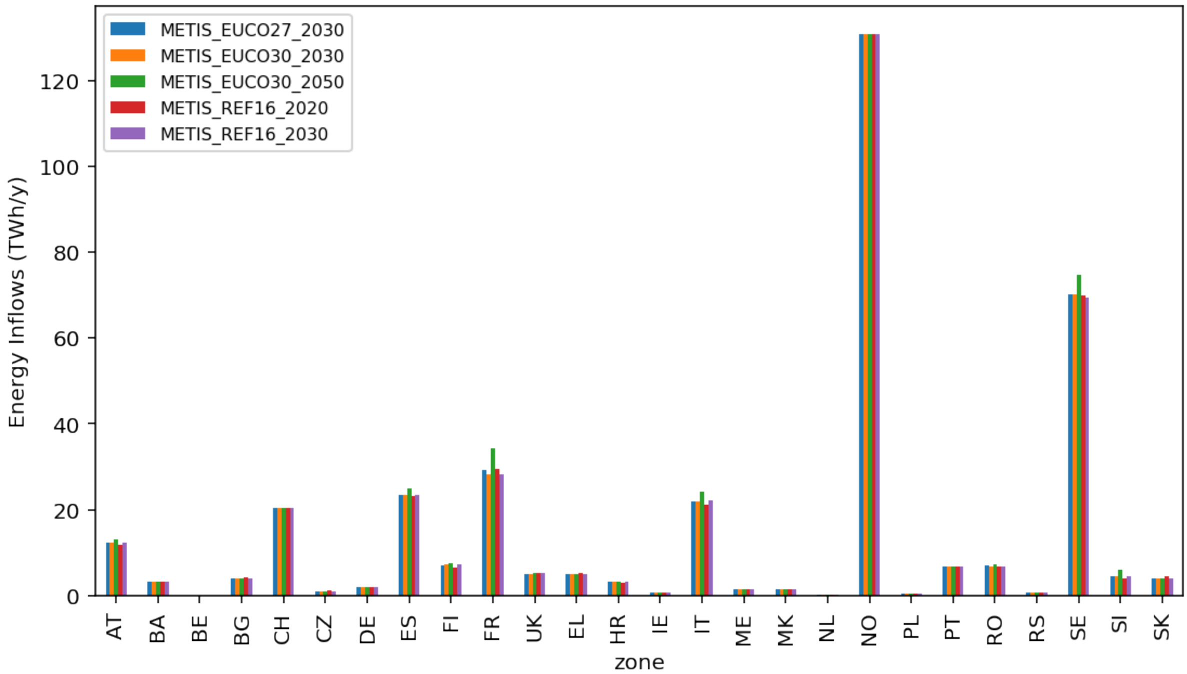
Annex 3. Hydro inflows comparison

Hydro inflows vary year by year, and throughout the year, so it is important to have an accurate representation not only for a single year but also for extreme scenarios. This section analyses the available hydro inflow time series and compares them to the ones already included in METIS. The following two sources were used:

- MKONLINE: dataset of historical time-series for hydro-related power system modelling, contract C.B685869 with Markedskraft ASA.
- Research project RESTORE2050 (Alexander Kies, Lueder von Bremen, & Detlev Heinemann. (2017). Hydro Energy Inflow for Power System Studies [Data set]. Zenodo. http://doi.org/10.5281/zenodo.804244)

The following figure shows the hydro inflows available in METIS at the beginning of the project and before the calibration, taken from different energy projections.

Figure 23 Different scenarios of annual hydro inflows in the scenarios based on the time series available in METIS before the calibration



We compare a single year of METIS with the distribution of years from the two datasets; single year of METIS compared to the distribution of all years available of MKONLINE (Fig. 19) and single year of METIS compare to the distribution of all years available in RESTORE2050 (Fig. 20). As the annual levels do not differ much we pick the scenario called REF16_2020 for this comparison. In most cases annual levels fall into the range of inflows but some countries like DE, CH, FR, IT are significantly different when compared with other datasets.

Figure 24 Comparison of annual values of inflows time series. precalibrated current context (red dot for year 2014) vs RESTORE2050 (distribution of years 2003 – 2012)

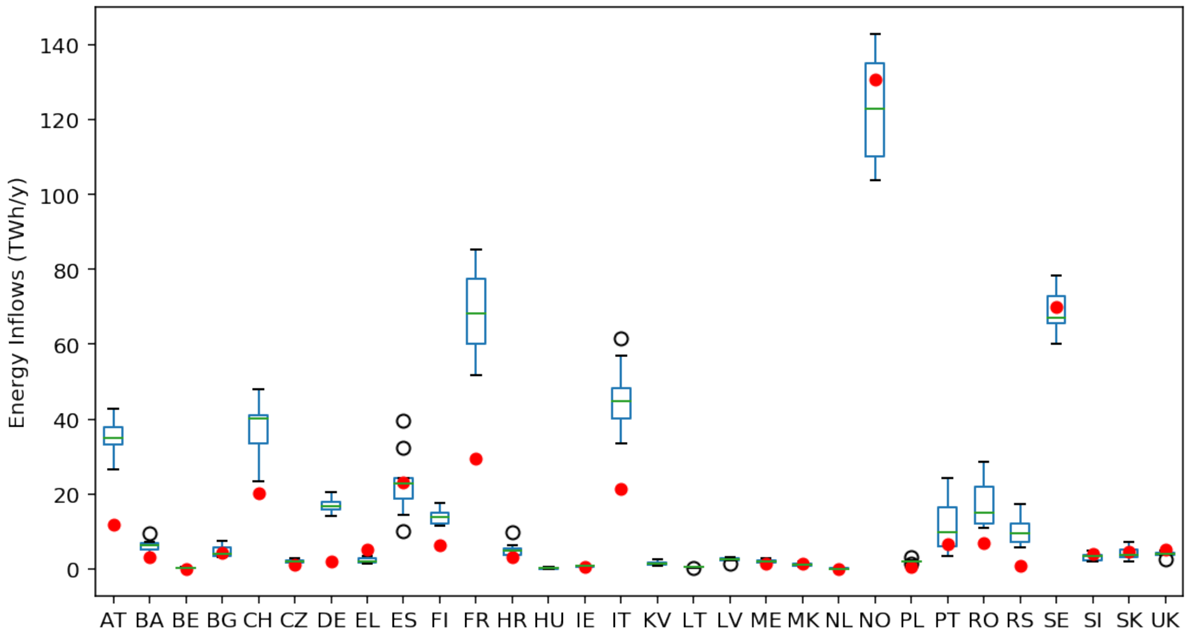
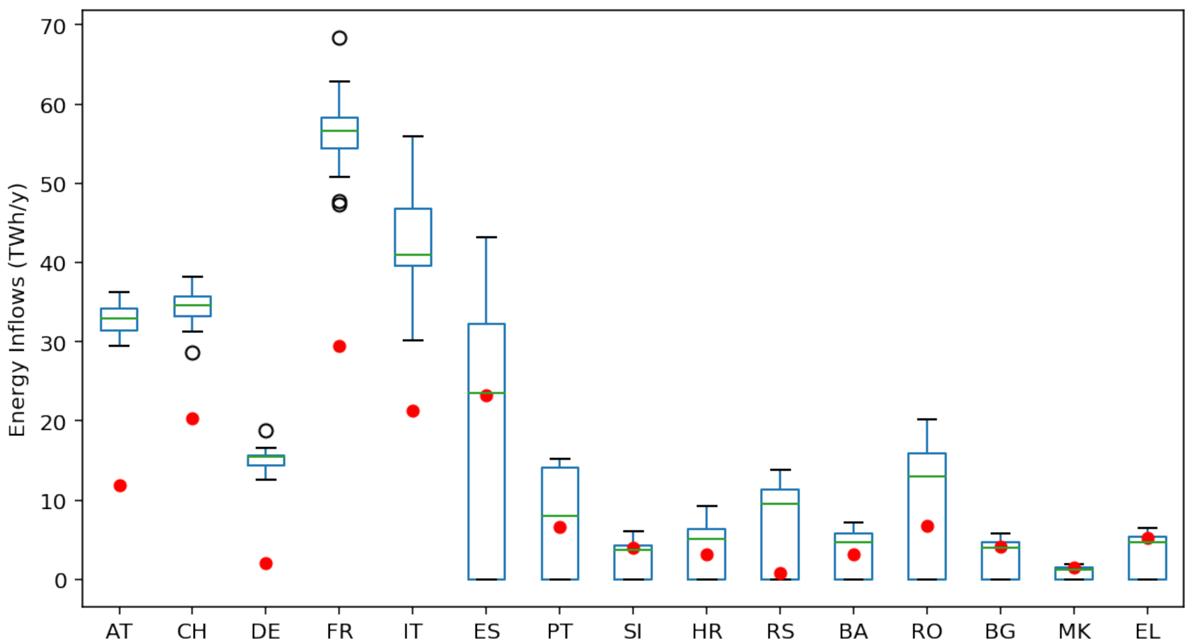


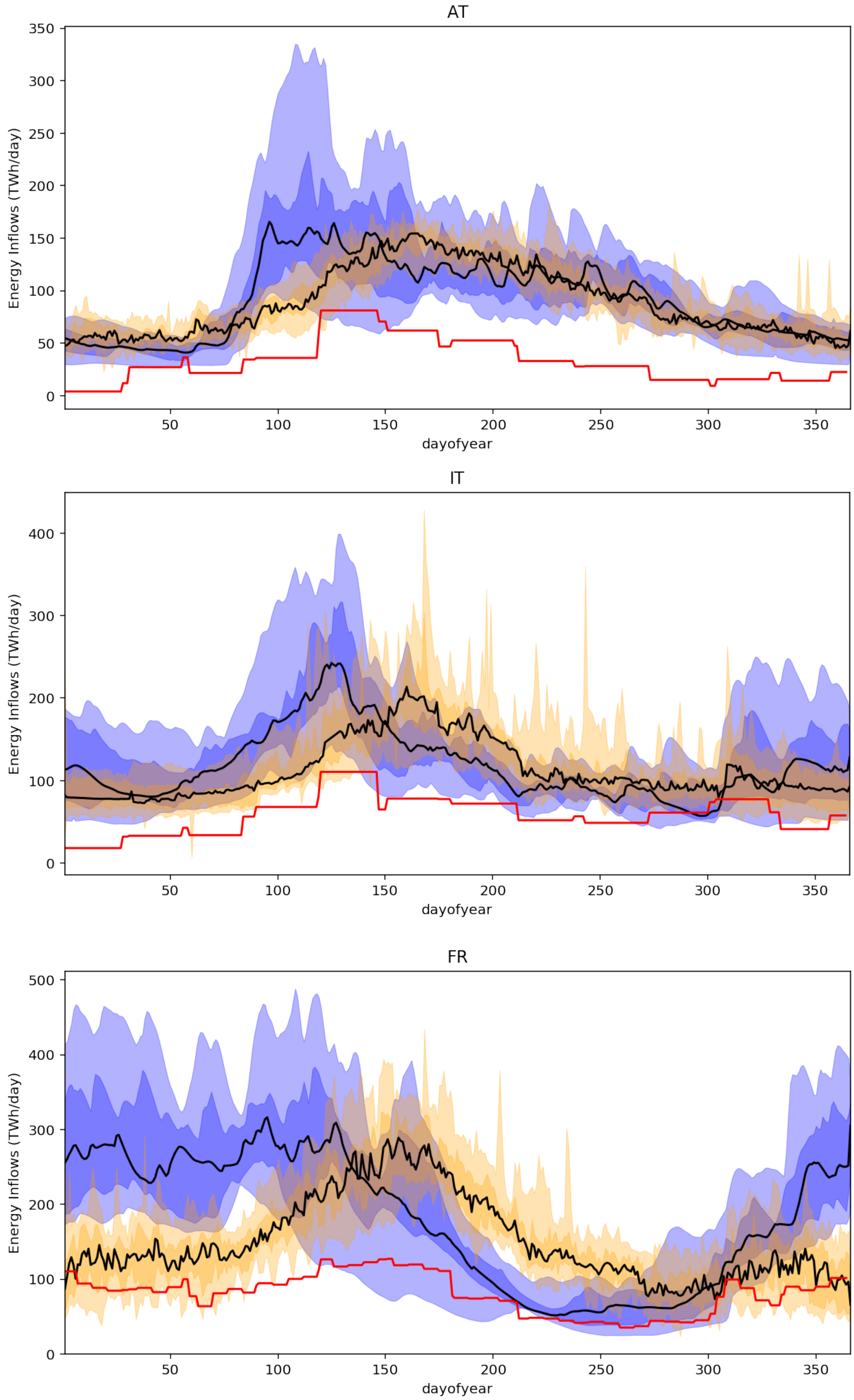
Figure 25 Comparison of annual values of inflows time series. precalibrated current context (red dot for year 2014) vs MKONLINE (distribution of years 2004 – 2015)



Temporal evolution

The annual patterns of the three datasets are also compared to see their correspondence in terms of peaks and ramps. Most countries differ significantly as they are based on different approaches, e.g. RESTORE2050 is based on real precipitation and geographical heights. Currently METIS timeseries are estimated on a weekly level. In future work, METIS can benefit from the highest resolution of the datasets described for a more accurate inflow representation.

Figure 26. One year time series for the case of Austria, Italy, France. precalibrated current context in red, RESTORE2050 in blue (median, 95%, 5% percentile) and MKONLINE in orange (median, 95%, 5% percentile)



Annex 4. Thermal power plant availabilities

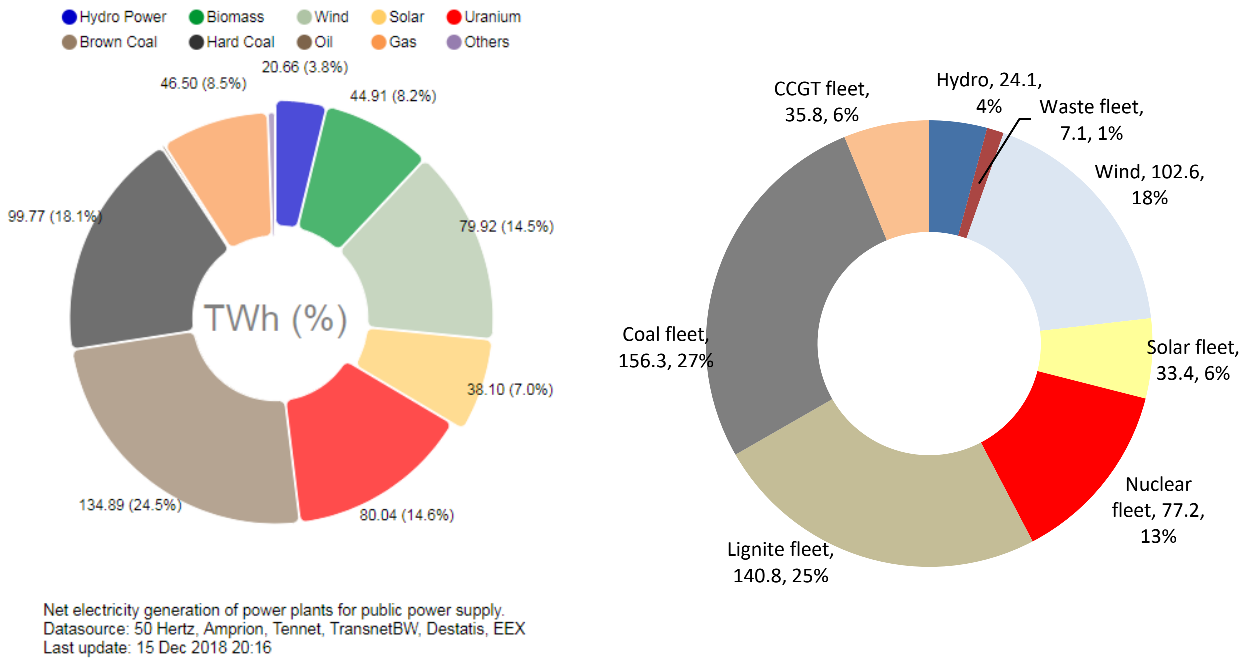
Table 16. Comparison of average fleet availabilities per country. Please note that for Lignite, Coal and CCGT fleet METIS by default uses one availability time series per fleet.

	Nuclear Fleet		**Lignite Fleet**		**Coal Fleet**		**CCGT Fleet**	
Country	**ENTSO-E**	**METIS**	**ENTSO-E**	**METIS**	**ENTSO-E**	**METIS**	**ENTSO-E**	**METIS**
AT					1.00	0.81	1.00	0.82
BE	0.75	0.93					1.00	0.82
BG	0.89	0.87	0.91	0.86	1.00	0.81		0.82
CH	0.71	0.90						0.82
CZ	0.71	0.85	0.63	0.86	1.00	0.81	1.00	0.82
DE	0.79	0.81	0.95	0.86	0.96	0.81	0.97	0.82
DK					0.99	0.81	0.96	0.82
EE			0.89	0.86				
ES	0.87	0.90			1.00	0.81	0.99	0.82
FI	0.95	0.93	0.67	0.86	1.00	0.81	1.00	0.82
FR	0.81	0.81			0.98	0.81	0.99	0.82
EL			0.82	0.86				
HU	0.83	0.85	0.72	0.86			1.00	0.82
IE			0.86	0.86	0.90	0.81	0.92	0.82
IT					1.00	0.81	0.98	0.82
LT							1.00	0.82
LV							1.00	0.82
NL	1.00	0.89			0.97	0.81	1.00	0.82
NO							1.00	0.82
PL			0.95	0.86	0.99	0.81	0.99	0.82
PT					1.00	0.81	1.00	0.82
RO	0.90	0.94	0.65	0.86	0.98	0.81	0.99	0.82
RS			0.76	0.86				
SE	0.93	0.85					1.00	0.82
SI	0.82	0.92	0.79	0.86				
SK	0.89	0.90	0.92	0.86	1.00	0.81	1.00	0.82
UK	0.92	0.89			0.95	0.81	0.97	0.82

Annex 5. Current context calibration

The current context was created and some preliminary runs revealed not large inconsistencies for the case of Germany randomly selected and benchmarked against published annual electricity generation fuel mix for 2016[26]

Figure 27. Comparison of actual annual fuel mix and METIS 1st simulation results for 2016 (based on EMHIRES time series corresponding to climatic conditions observed in 1986)



Similarly a qualitative comparison between the actual dispatching in week 51 of 2016 and the results from METIS revealed a fairly good first approximation.

26 https://www.energy-charts.de/energy_pie.htm?year=2016

Figure 28. Electricity production in Germany in week 51 2016[27]

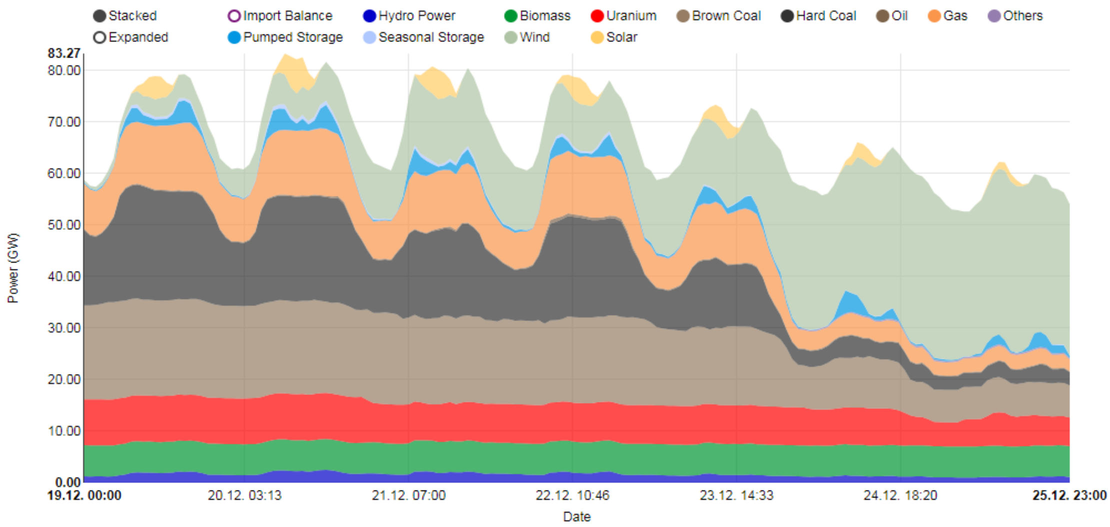


Figure 29. Initial simulation results Germany, week 51

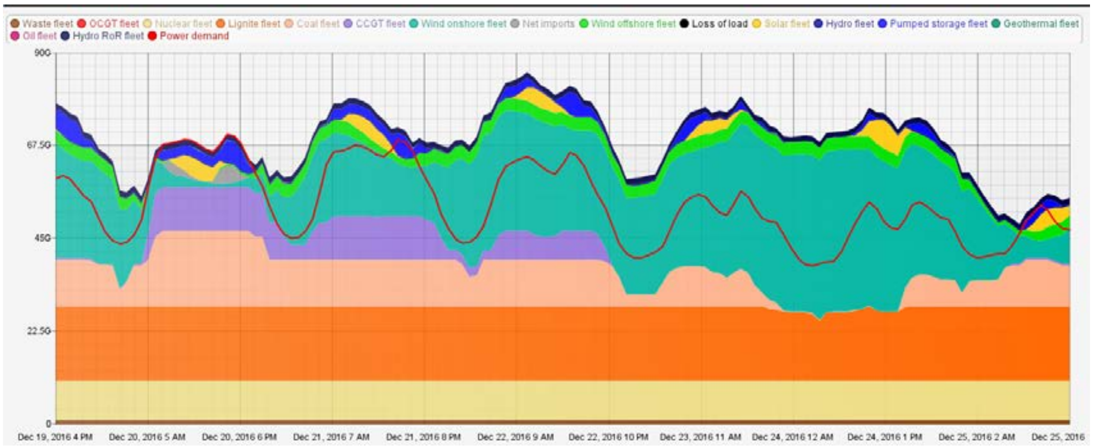
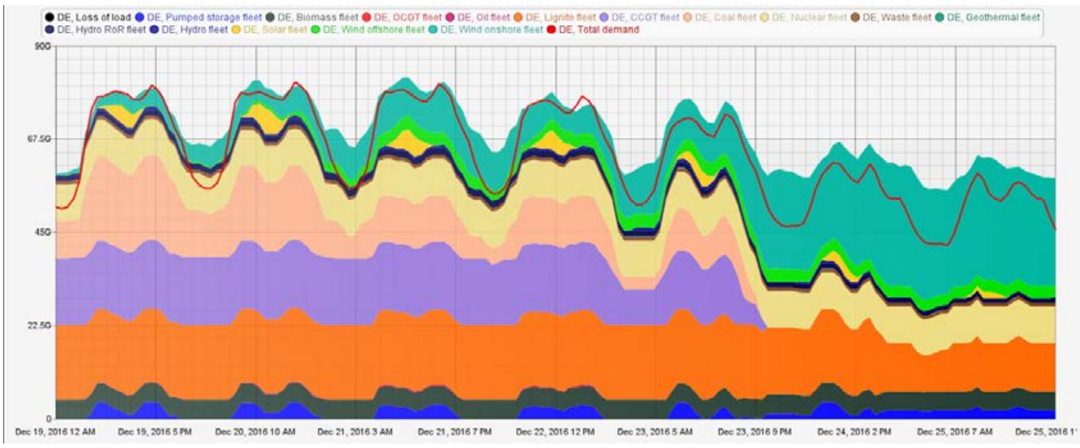


Figure 30. Final simulation results, Germany, week 51



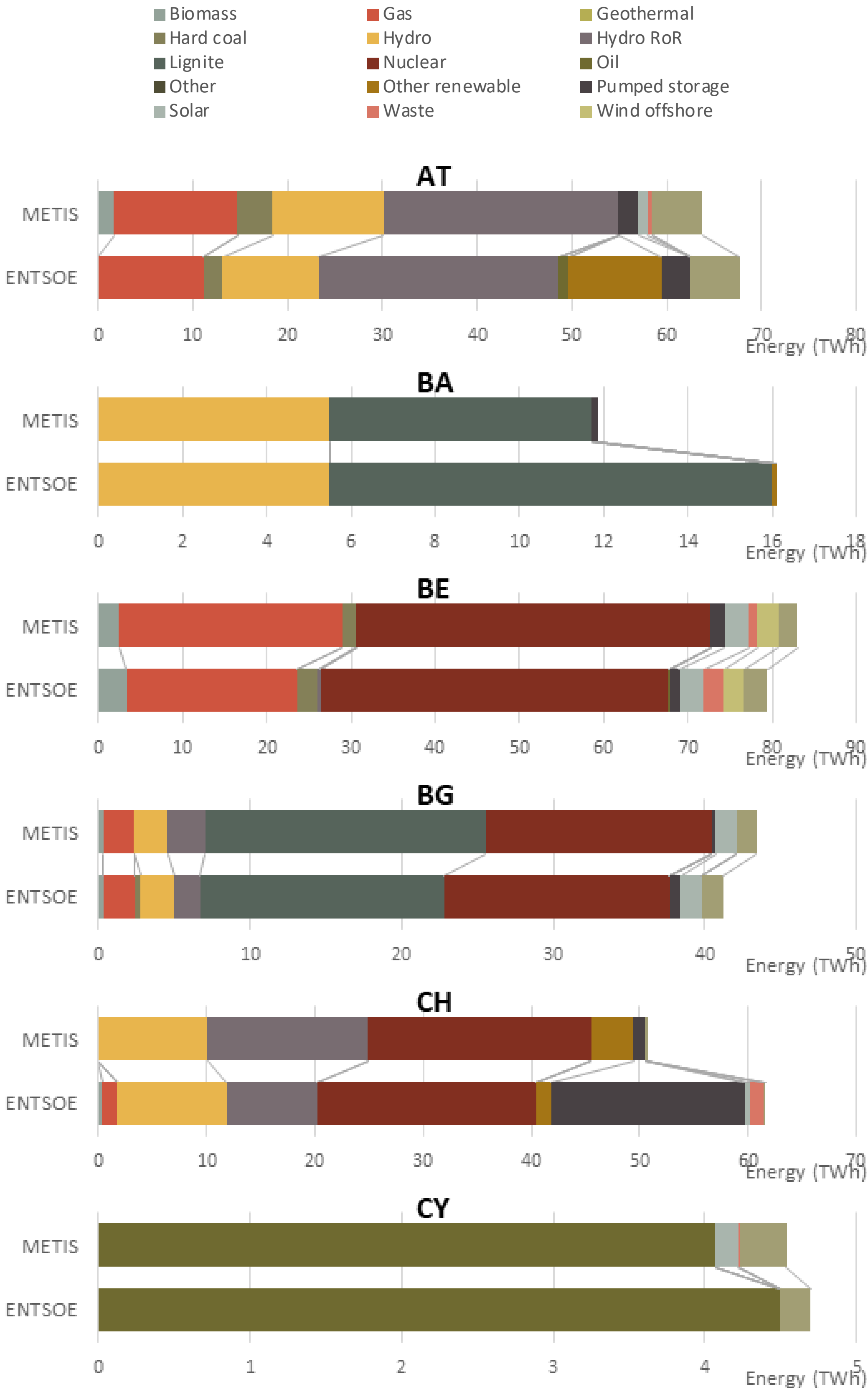
27 Source: Fraunhofer ISE https://www.energy-charts.de

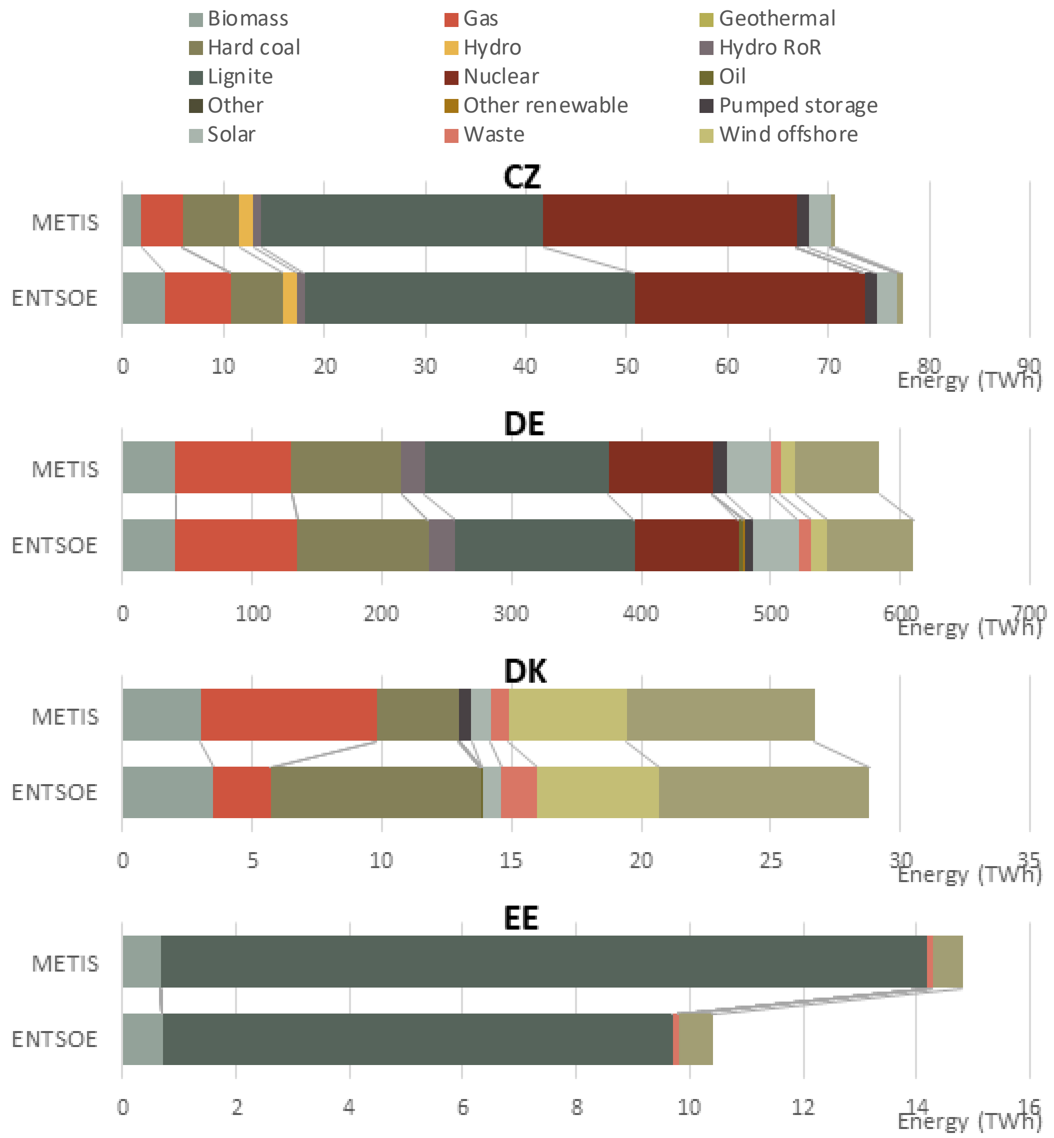
Annex 6. Net import comparison (actual vs modelled)

Table 17. Comparison of net imports: ENTSO-E SF 2016 vs. METIS results at country level (TWh)

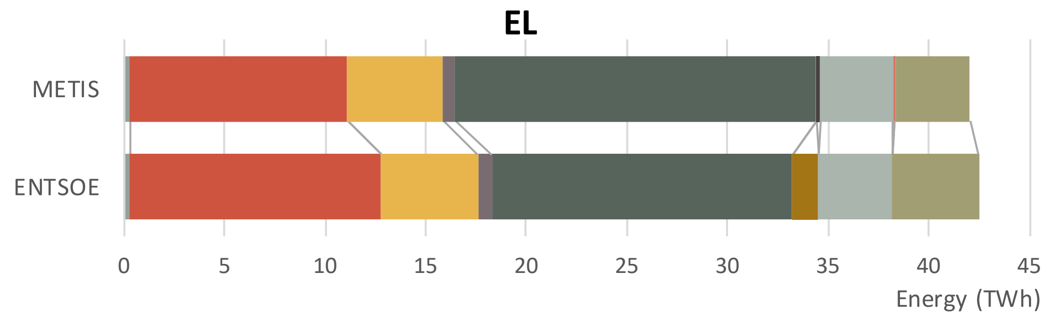
Country	ENTSO-E SF 2016	METIS CC 2016	Absolute difference	Difference
DE	-53.74	-22.72	31.02	-31.02
FR	-40.98	-45.27	4.29	4.29
FI	19.01	17.50	1.51	1.51
CZ	-10.97	-4.27	6.70	-6.70
PL	2.00	9.97	7.97	-7.97
HU	12.73	7.44	5.29	5.29
UK	18.91	9.30	9.61	9.61
NL	5.19	-4.82	10.01	10.01
ES	7.67	12.48	4.81	-4.81
BA	-3.76	-0.74	3.02	-3.02
BG	-6.36	-9.34	2.98	2.98
DK	5.29	8.54	3.25	-3.25
NO	-15.93	-18.79	2.86	2.86
SI	-1.06	-3.51	2.45	2.45
MK	2.05	-0.12	2.17	2.17
HR	6.34	9.20	2.86	-2.86
PT	-5.09	-9.13	4.04	4.04
CH	4.43	13.66	9.23	-9.23
LV	1.04	1.84	0.80	-0.80
SK	2.65	1.72	0.93	0.93
IT	36.90	33.30	3.60	3.60
RS	-2.32	-3.17	0.85	0.85
RO	-5.02	-7.35	2.33	2.33
IE	-0.69	-0.95	0.26	0.26
EL	8.80	9.52	0.72	-0.72
ME	0.30	-0.05	0.35	0.35
AT	8.72	9.10	0.38	-0.38
EE	-2.04	-6.41	4.37	4.37
BE	6.20	3.33	2.87	2.87
LU	6.31	6.33	0.02	-0.02
SE	-12.04	-14.98	2.94	2.94
LT	8.27	8.05	0.22	0.22

Annex 7. Country fuel mix (actual vs modelled)

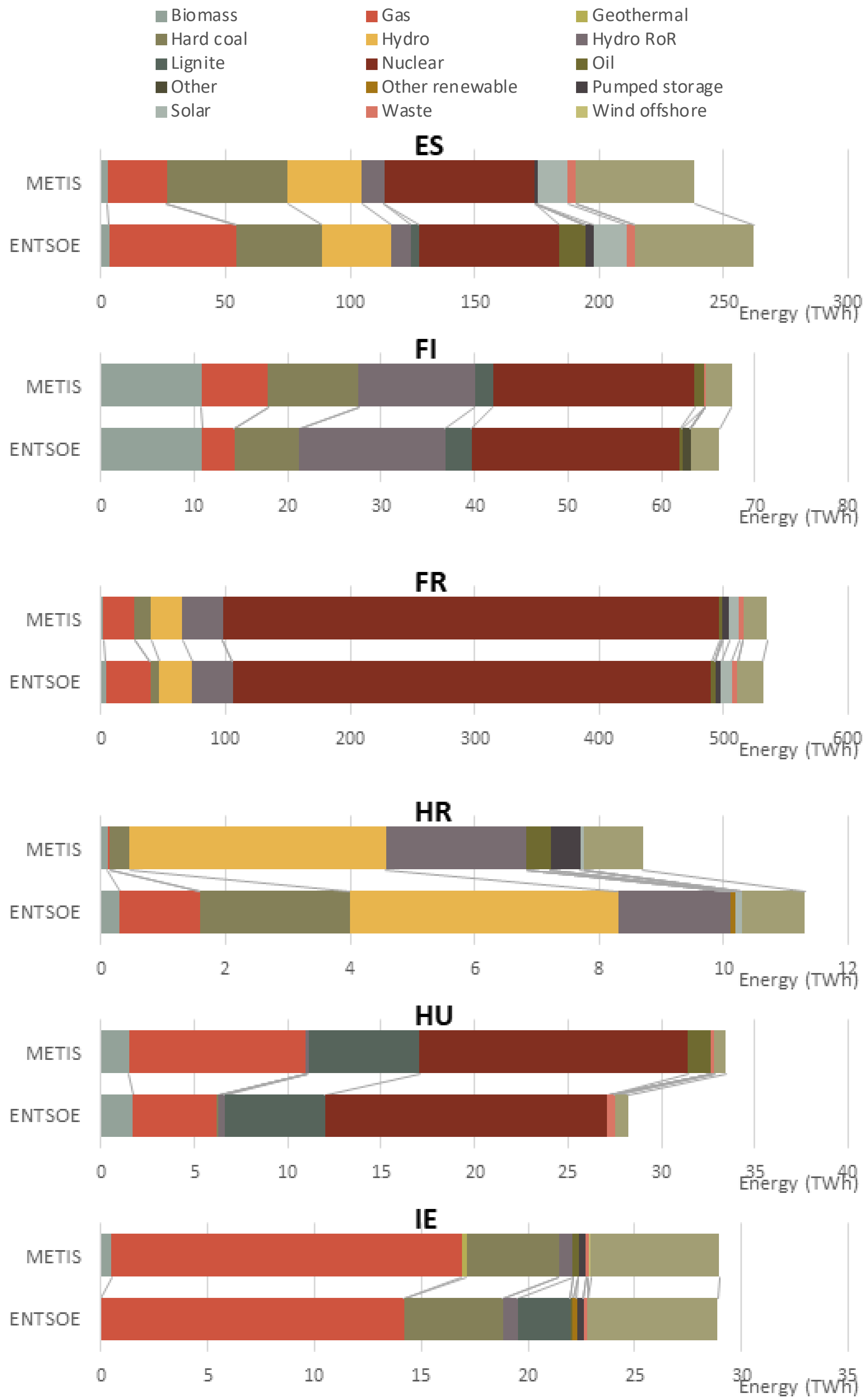




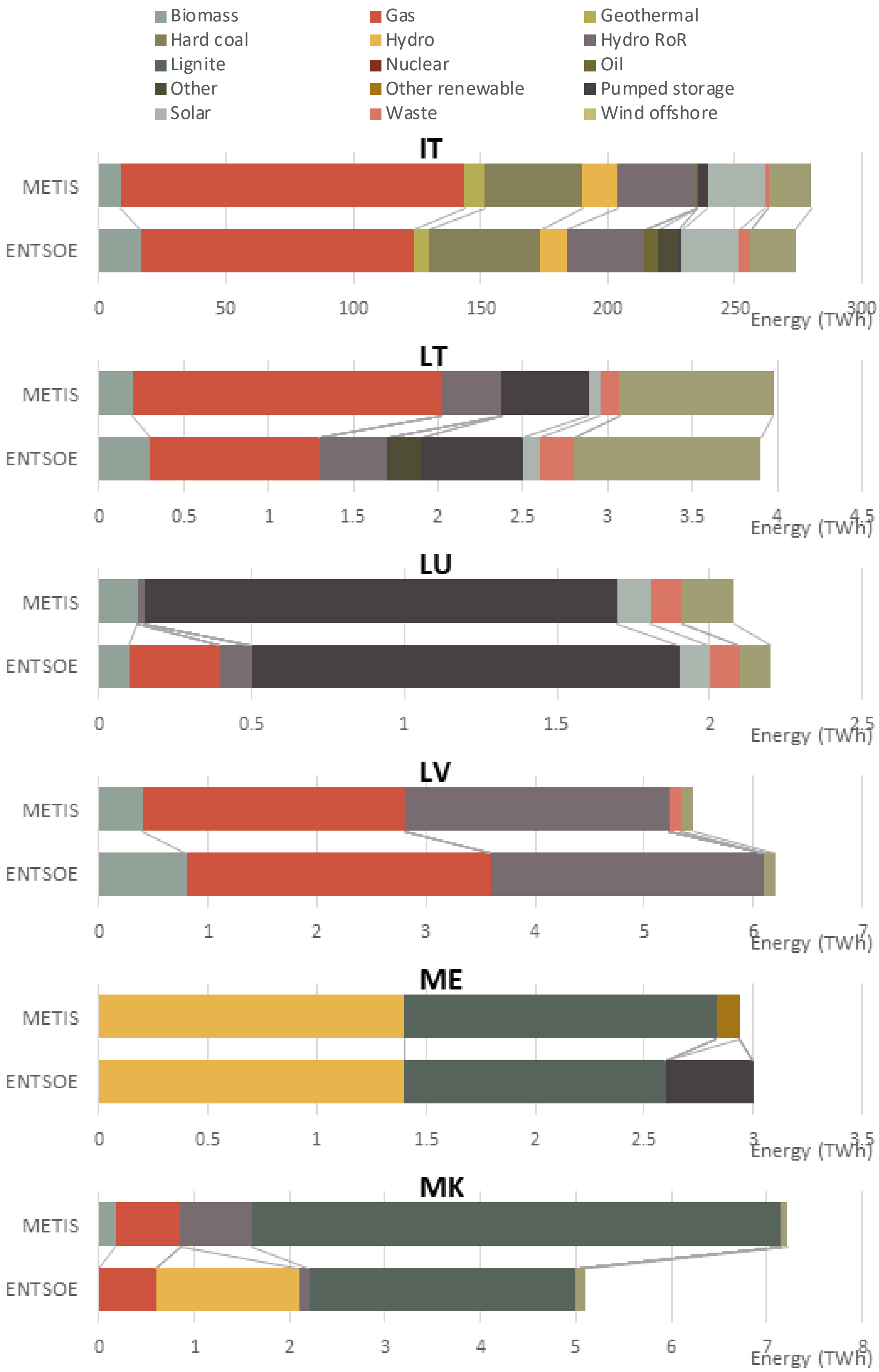
Note : EE : Coal is oil shale

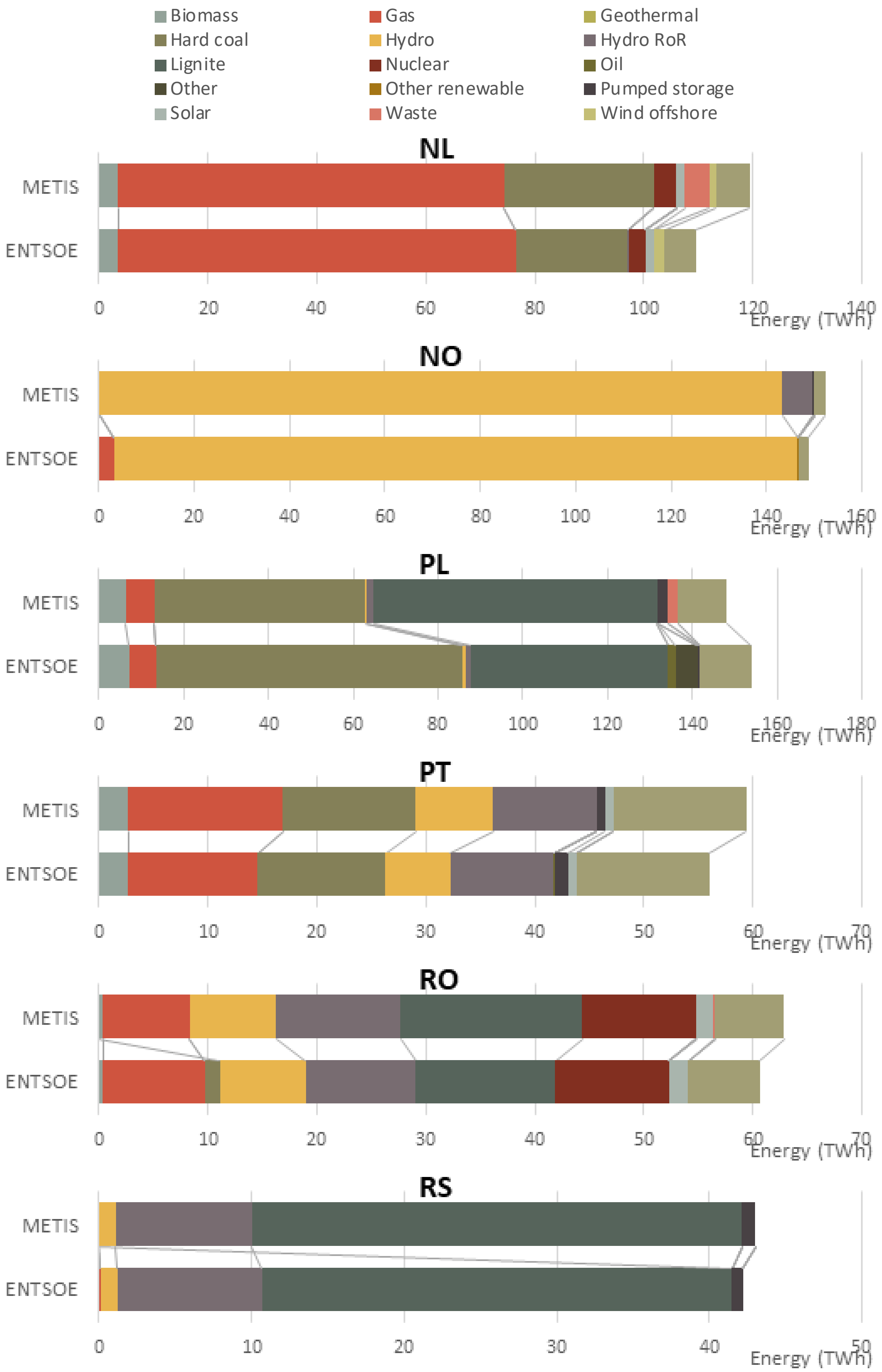


Note : Coal is lignite

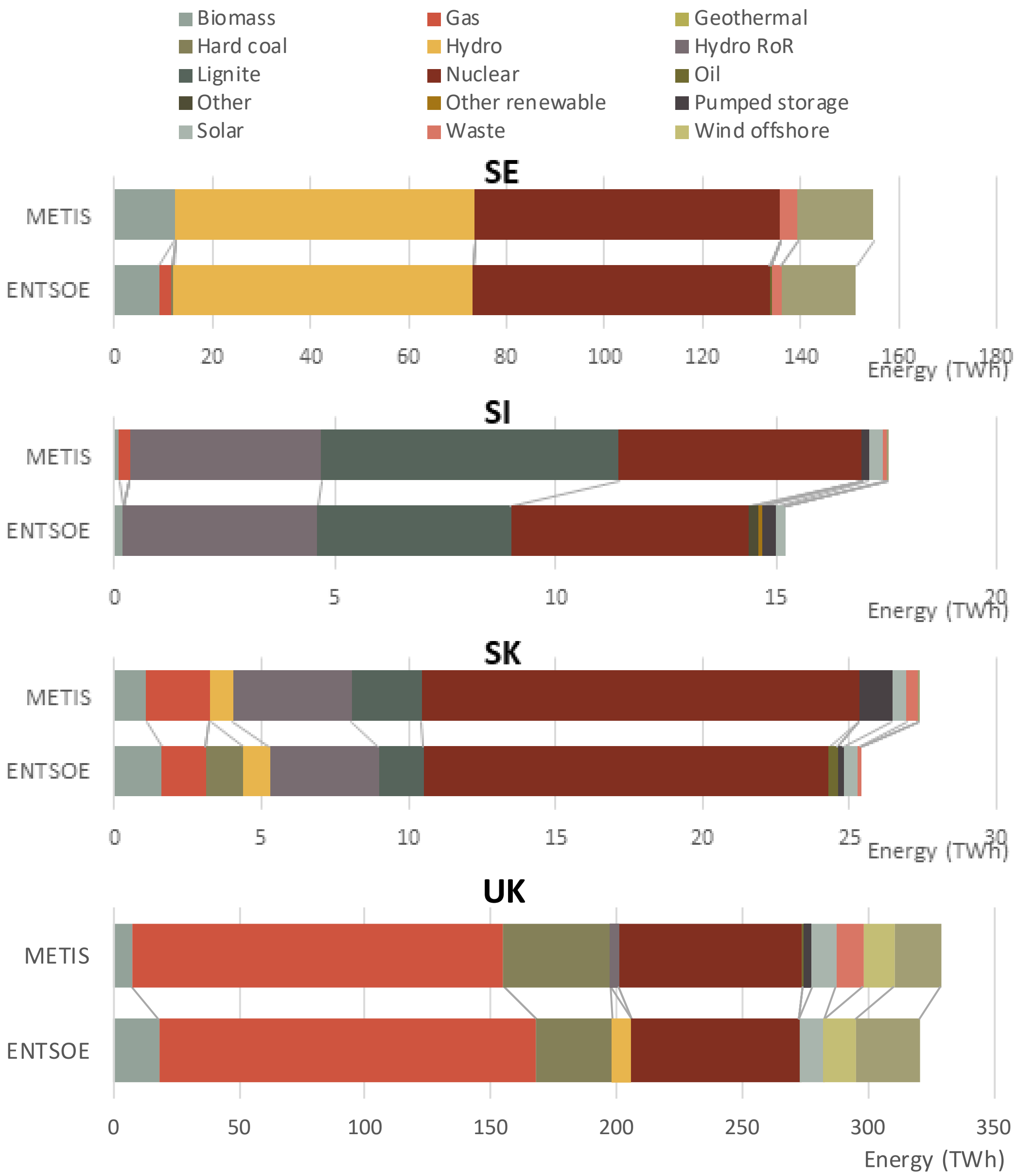


Biomass
Gas
Geothermal
Hard coal
Hydro
Hydro RoR
Lignite
Nuclear
Oil
Other
Other renewable
Pumped storage
Solar
Waste
Wind offshore
ES
METIS
ENTSOE
0 50 100 150 200 250 300
Energy (TWh)
FI
METIS
ENTSOE
0 10 20 30 40 50 60 70 80
Energy (TWh)
FR
METIS
ENTSOE
0 100 200 300 400 500 600
Energy (TWh)
HR
METIS
ENTSOE
0 2 4 6 8 10 12
Energy (TWh)
HU
METIS
ENTSOE
0 5 10 15 20 25 30 35 40
Energy (TWh)
IE
METIS
ENTSOE
0 5 10 15 20 25 30 35
Energy (TWh)


Biomass
Gas
Geothermal
Hard coal
Hydro
Hydro RoR
Lignite
Nuclear
Oil
Other
Other renewable
Pumped storage
Solar
Waste
Wind offshore
IT
METIS
ENTSOE
0 50 100 150 200 250 300
Energy (TWh)
LT
METIS
ENTSOE
0 0.5 1 1.5 2 2.5 3 3.5 4 4.5
Energy (TWh)
LU
METIS
ENTSOE
0 0.5 1 1.5 2 2.5
Energy (TWh)
LV
METIS
ENTSOE
0 1 2 3 4 5 6 7
Energy (TWh)
ME
METIS
ENTSOE
0 0.5 1 1.5 2 2.5 3 3.5
Energy (TWh)
MK
METIS
ENTSOE
0 1 2 3 4 5 6 7 8
Energy (TWh)

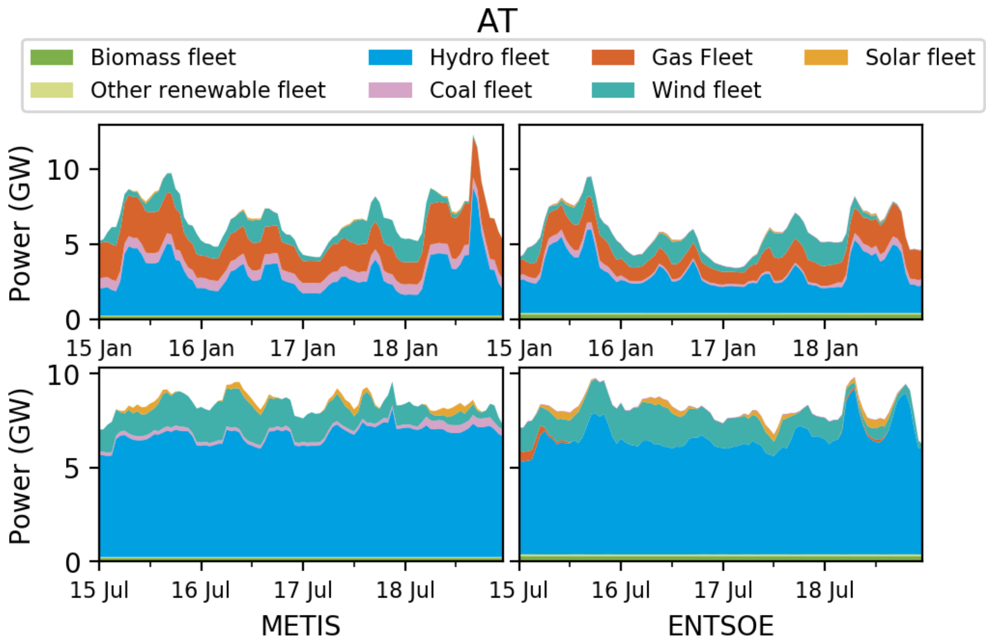


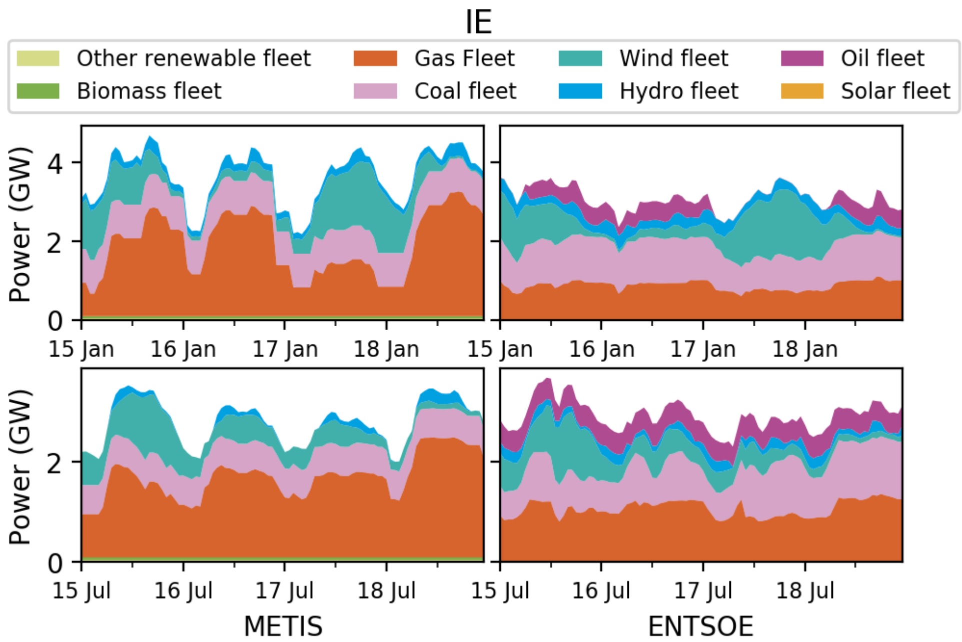
Biomass
Gas
Geothermal
Hard coal
Hydro
Hydro RoR
Lignite
Nuclear
Oil
Other
Other renewable
Pumped storage
Solar
Waste
Wind offshore
NL
METIS
ENTSOE
0 20 40 60 80 100 120 140
Energy (TWh)
NO
METIS
ENTSOE
0 20 40 60 80 100 120 140 160
Energy (TWh)
PL
METIS
ENTSOE
0 20 40 60 80 100 120 140 160 180
Energy (TWh)
PT
METIS
ENTSOE
0 10 20 30 40 50 60 70
Energy (TWh)
RO
METIS
ENTSOE
0 10 20 30 40 50 60 70
Energy (TWh)
RS
METIS
ENTSOE
0 10 20 30 40 50
Energy (TWh)

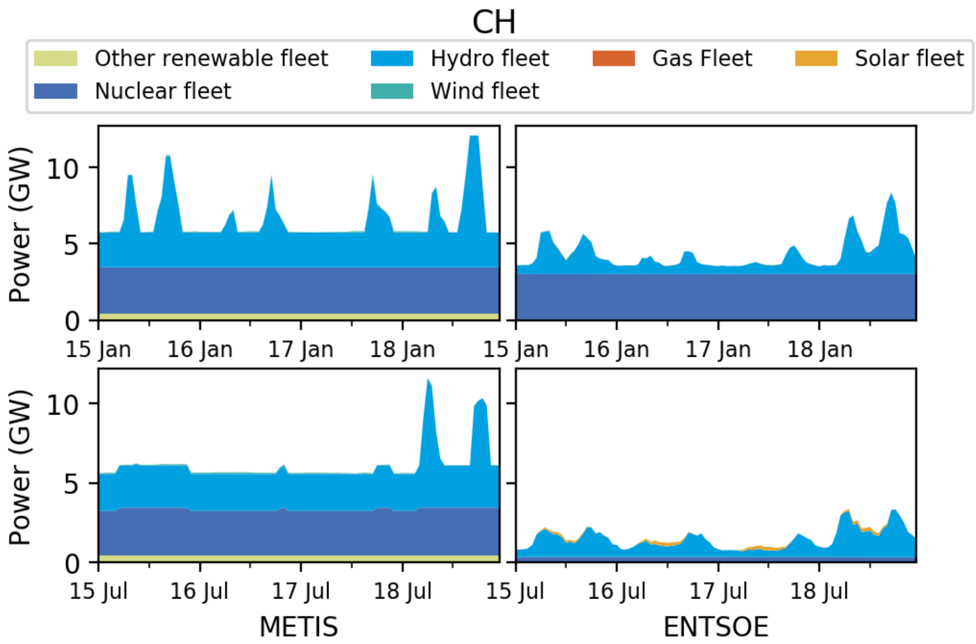

Biomass
Gas
Geothermal
Hard coal
Hydro
Hydro RoR
Lignite
Nuclear
Oil
Other
Other renewable
Pumped storage
Solar
Waste
Wind offshore
SE
METIS
ENTSOE
0 20 40 60 80 100 120 140 160 180
Energy (TWh)
SI
METIS
ENTSOE
0 5 10 15 20
Energy (TWh)
SK
METIS
ENTSOE
0 5 10 15 20 25 30
Energy (TWh)
UK
METIS
ENTSOE
0 50 100 150 200 250 300 350
Energy (TWh)

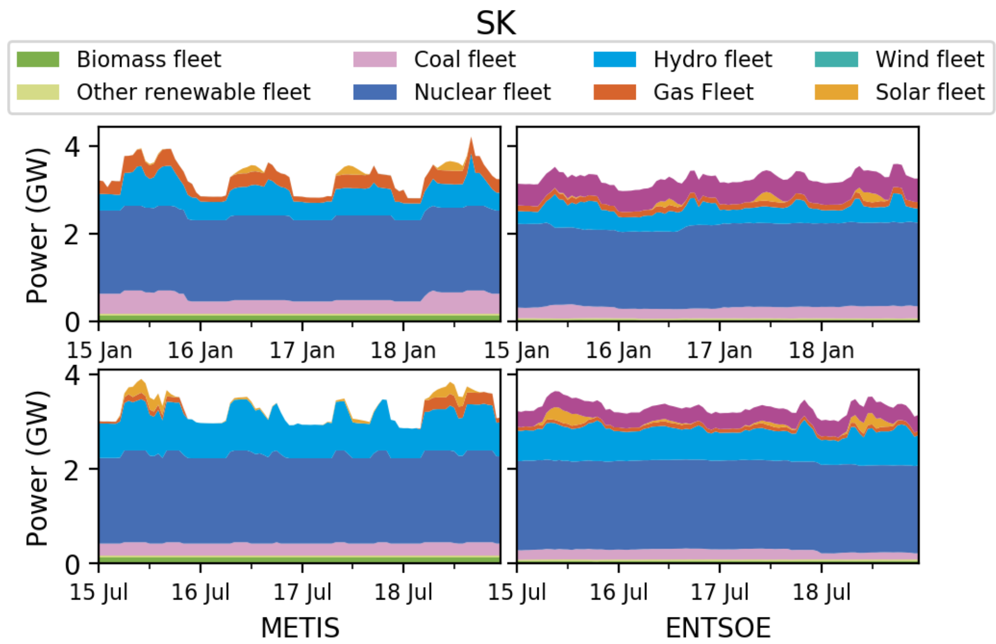
Annex 8. Typical dispatch day (winter summer).

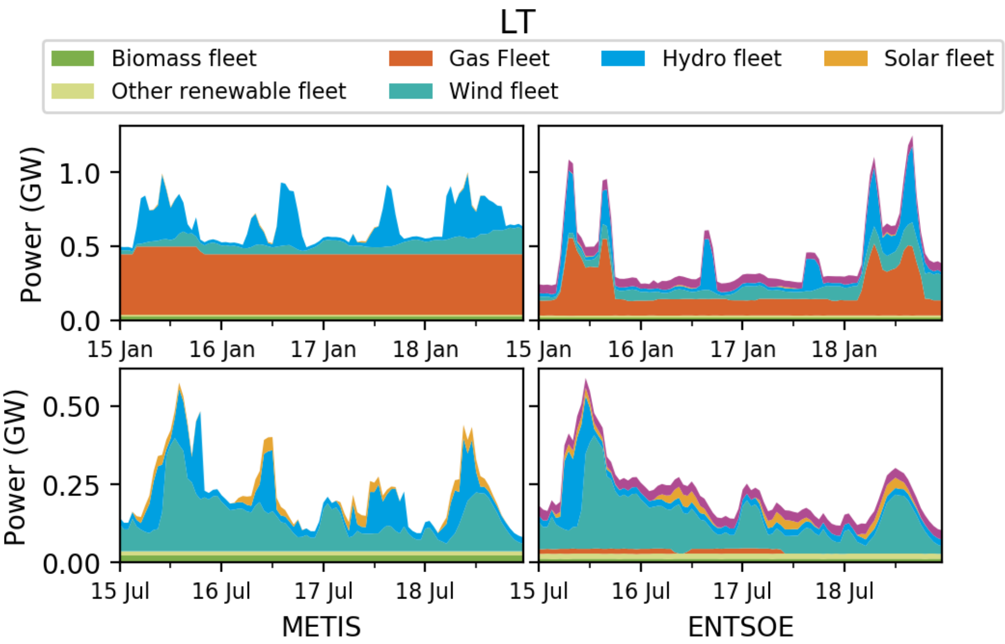
The simulation results (left) are compared with the real dispatch as mentioned in ENTSOE Transparency platform (right). A typical day in winter (top) and a typical day in summer (bottom) is shown.

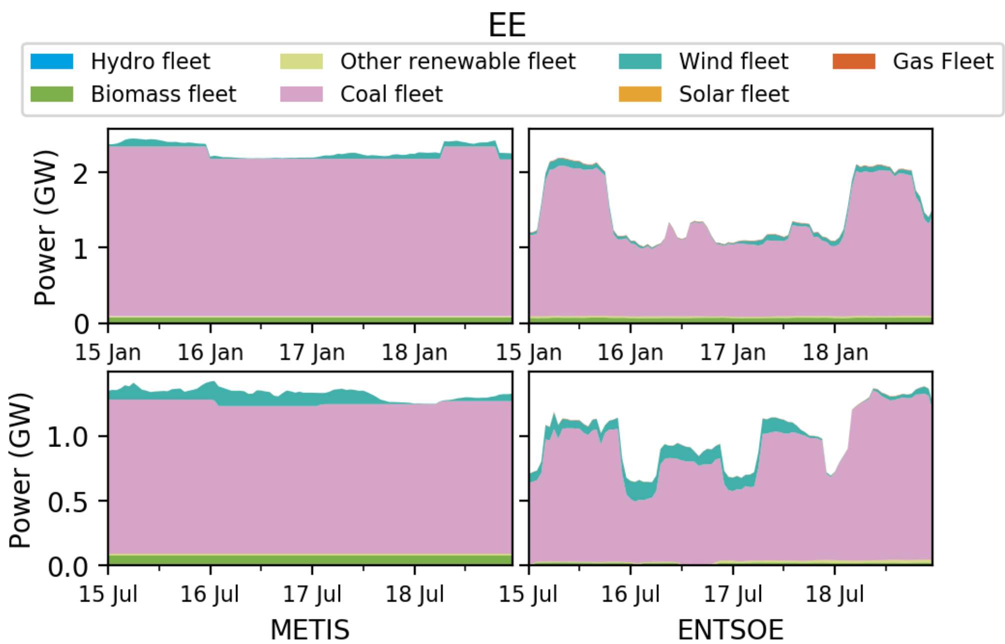




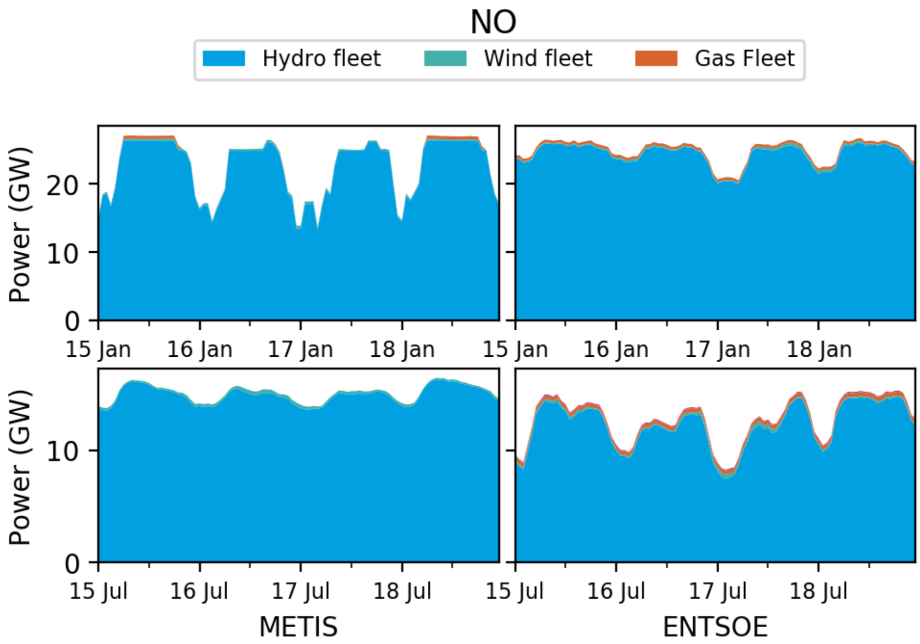

CH
Other renewable fleet
Hydro fleet
Gas Fleet
Solar fleet
Nuclear fleet
Wind fleet
Power (GW)
15 Jan
16 Jan
17 Jan
18 Jan
15 Jul
16 Jul
17 Jul
18 Jul
METIS
ENTSOE

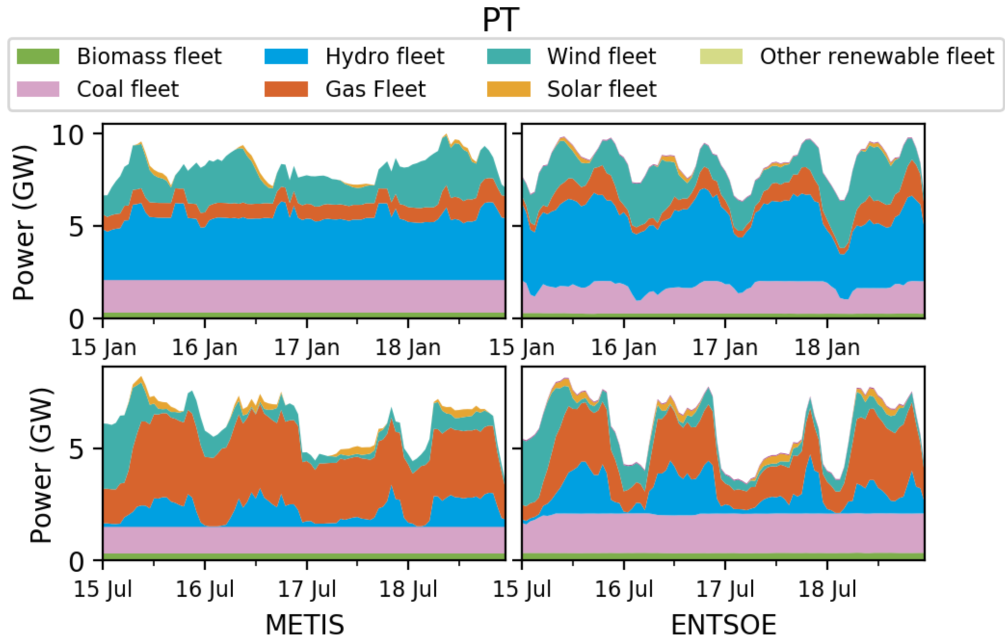

SK
Biomass fleet
Coal fleet
Hydro fleet
Wind fleet
Other renewable fleet
Nuclear fleet
Gas Fleet
Solar fleet
Power (GW)
15 Jan
16 Jan
17 Jan
18 Jan
15 Jul
16 Jul
17 Jul
18 Jul
METIS
ENTSOE

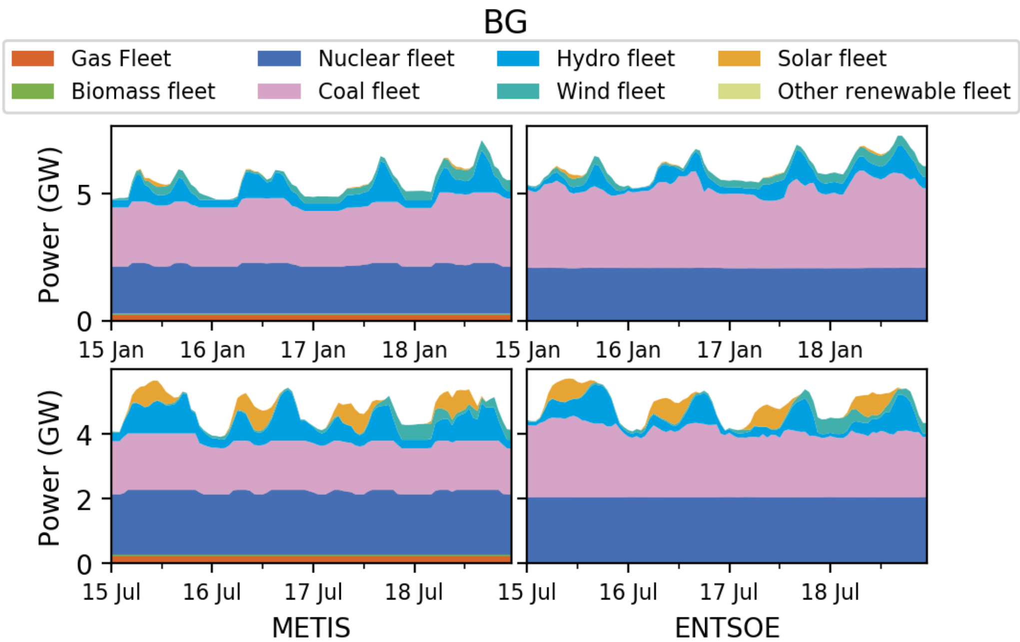


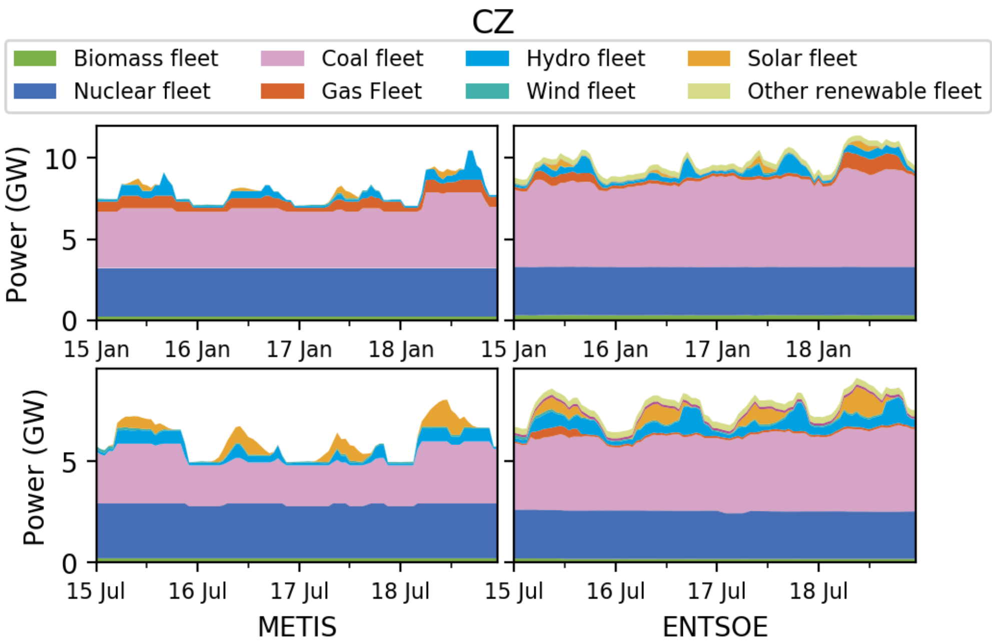


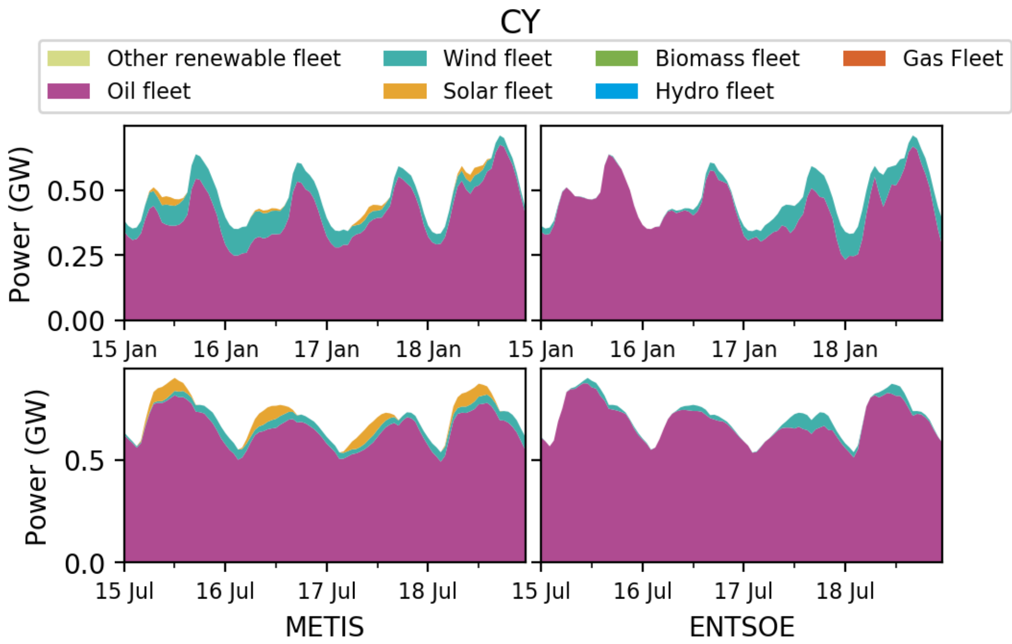
Note : Coal is oil shale


NO
Hydro fleet
Wind fleet
Gas Fleet
Power (GW)
20
10
0
15 Jan
16 Jan
17 Jan
18 Jan
Power (GW)
10
0
15 Jul
16 Jul
17 Jul
18 Jul
METIS
ENTSOE

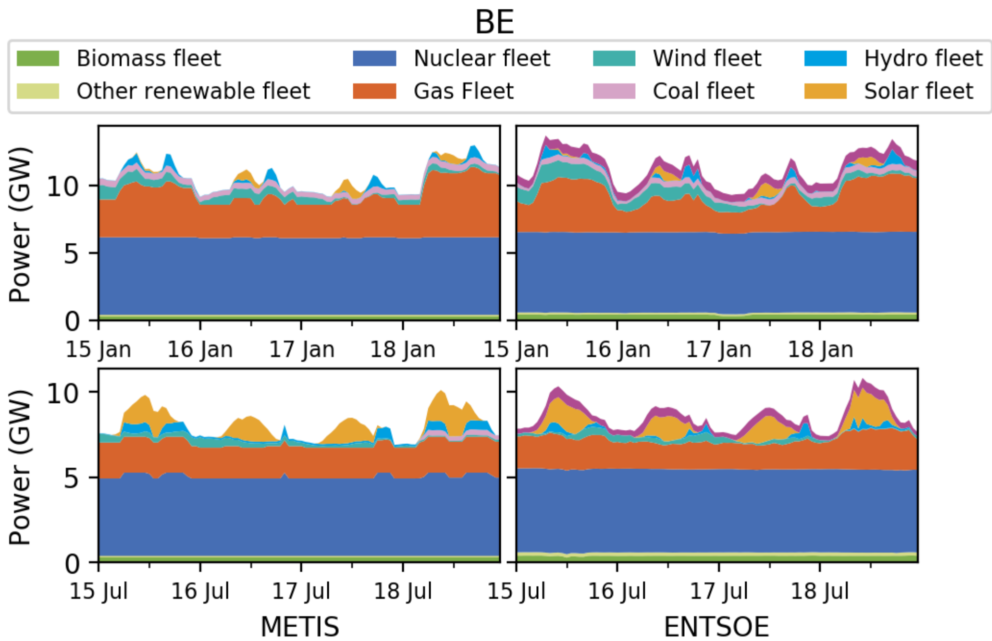

PT
Biomass fleet
Hydro fleet
Wind fleet
Other renewable fleet
Coal fleet
Gas Fleet
Solar fleet
Power (GW)
10
5
0
15 Jan
16 Jan
17 Jan
18 Jan
Power (GW)
5
0
15 Jul
16 Jul
17 Jul
18 Jul
METIS
ENTSOE


BG
Gas Fleet
Nuclear fleet
Hydro fleet
Solar fleet
Biomass fleet
Coal fleet
Wind fleet
Other renewable fleet
Power (GW)
0
5
15 Jan
16 Jan
17 Jan
18 Jan
Power (GW)
0
2
4
15 Jul
16 Jul
17 Jul
18 Jul
METIS
ENTSOE

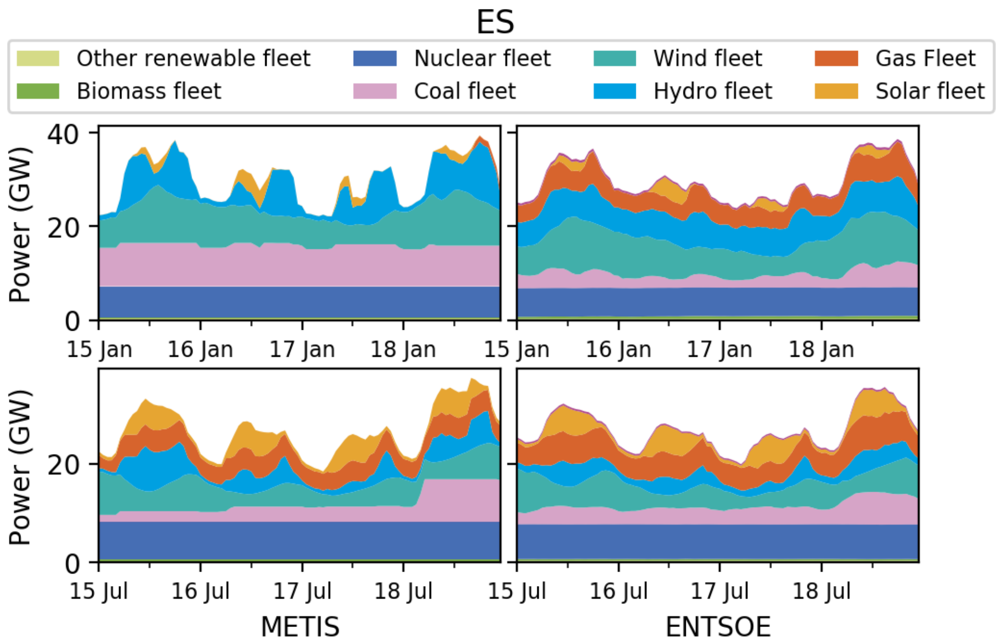

CZ
Biomass fleet
Coal fleet
Hydro fleet
Solar fleet
Nuclear fleet
Gas Fleet
Wind fleet
Other renewable fleet
Power (GW)
0
5
10
15 Jan
16 Jan
17 Jan
18 Jan
Power (GW)
0
5
15 Jul
16 Jul
17 Jul
18 Jul
METIS
ENTSOE

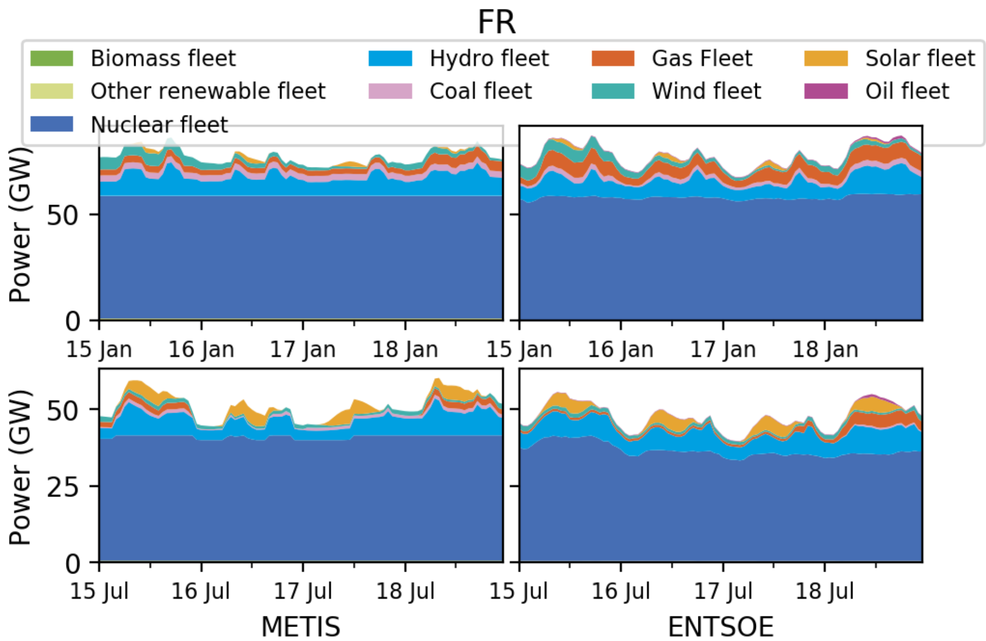


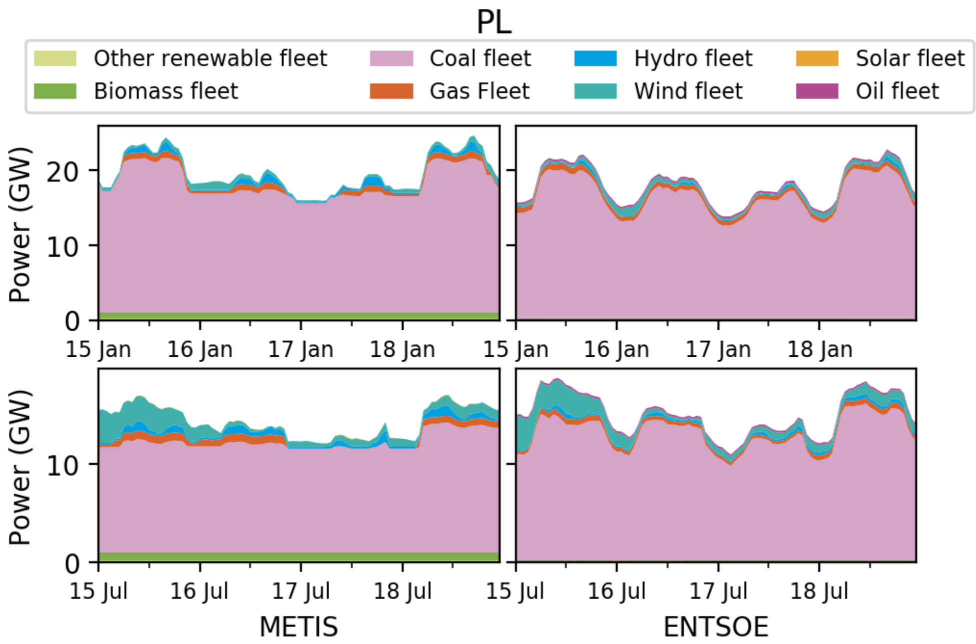
CY
Other renewable fleet
Wind fleet
Biomass fleet
Gas Fleet
Oil fleet
Solar fleet
Hydro fleet
Power (GW)
0.50
0.25
0.00
15 Jan
16 Jan
17 Jan
18 Jan
Power (GW)
0.5
0.0
15 Jul
16 Jul
17 Jul
18 Jul
METIS
ENTSOE

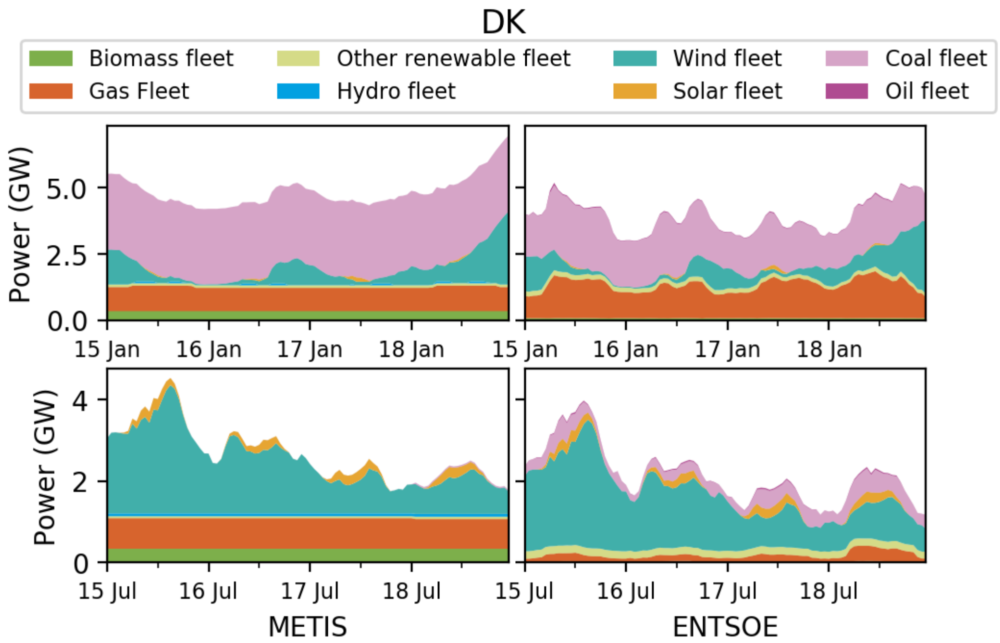


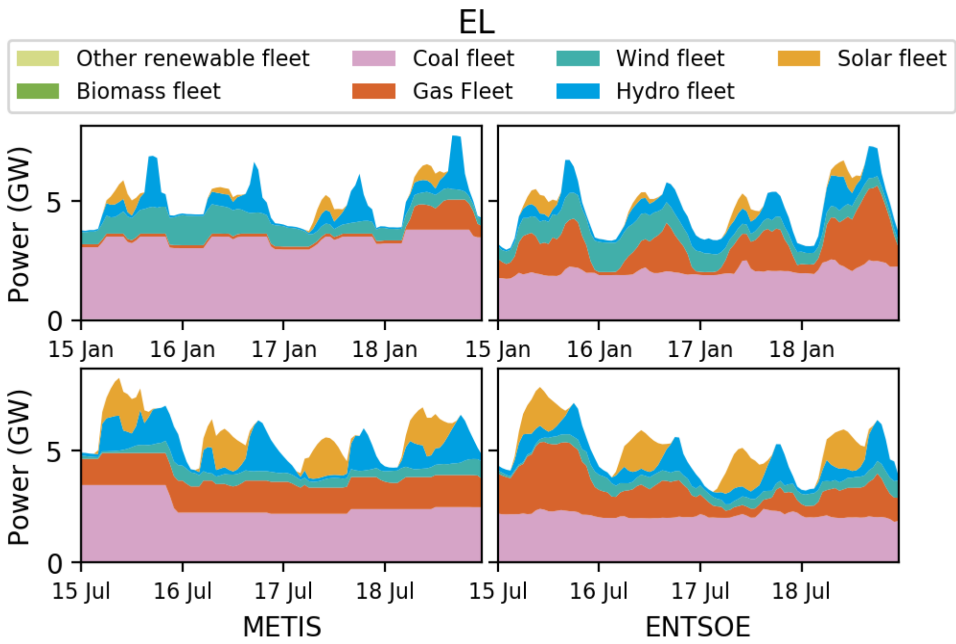
BE
Biomass fleet
Nuclear fleet
Wind fleet
Hydro fleet
Other renewable fleet
Gas Fleet
Coal fleet
Solar fleet
Power (GW)
10
5
0
15 Jan
16 Jan
17 Jan
18 Jan
Power (GW)
10
5
0
15 Jul
16 Jul
17 Jul
18 Jul
METIS
ENTSOE


ES
Other renewable fleet
Biomass fleet
Nuclear fleet
Coal fleet
Wind fleet
Hydro fleet
Gas Fleet
Solar fleet
Power (GW)
0
20
40
15 Jan
16 Jan
17 Jan
18 Jan
15 Jul
16 Jul
17 Jul
18 Jul
METIS
ENTSOE

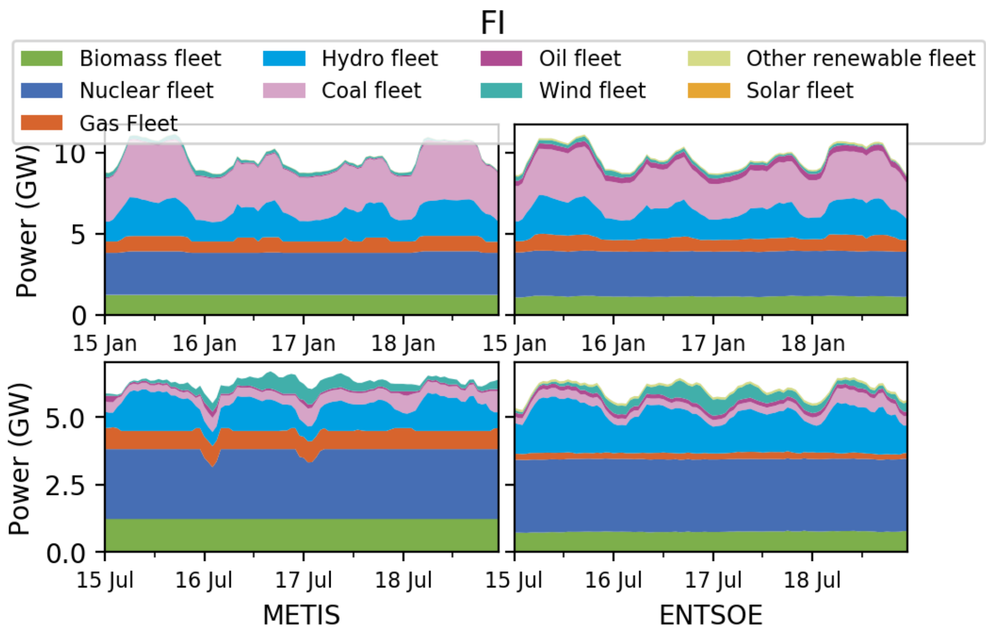

FR
Biomass fleet
Other renewable fleet
Nuclear fleet
Hydro fleet
Coal fleet
Gas Fleet
Wind fleet
Solar fleet
Oil fleet
Power (GW)
0
25
50
15 Jan
16 Jan
17 Jan
18 Jan
15 Jul
16 Jul
17 Jul
18 Jul
METIS
ENTSOE

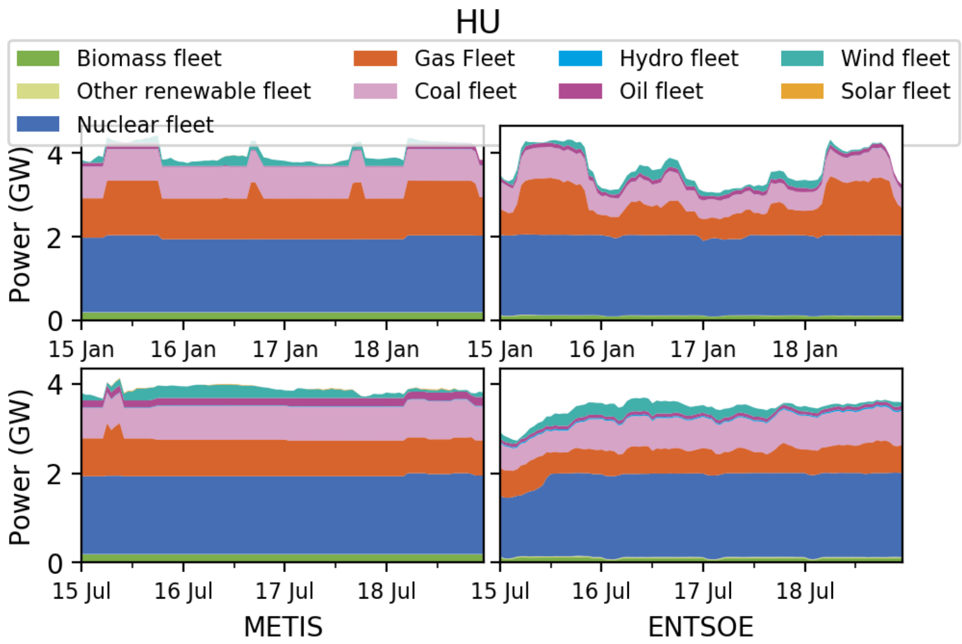

PL
Other renewable fleet
Biomass fleet
Coal fleet
Gas Fleet
Hydro fleet
Wind fleet
Solar fleet
Oil fleet
Power (GW)
0
10
20
15 Jan
16 Jan
17 Jan
18 Jan
Power (GW)
0
10
15 Jul
16 Jul
17 Jul
18 Jul
METIS
ENTSOE

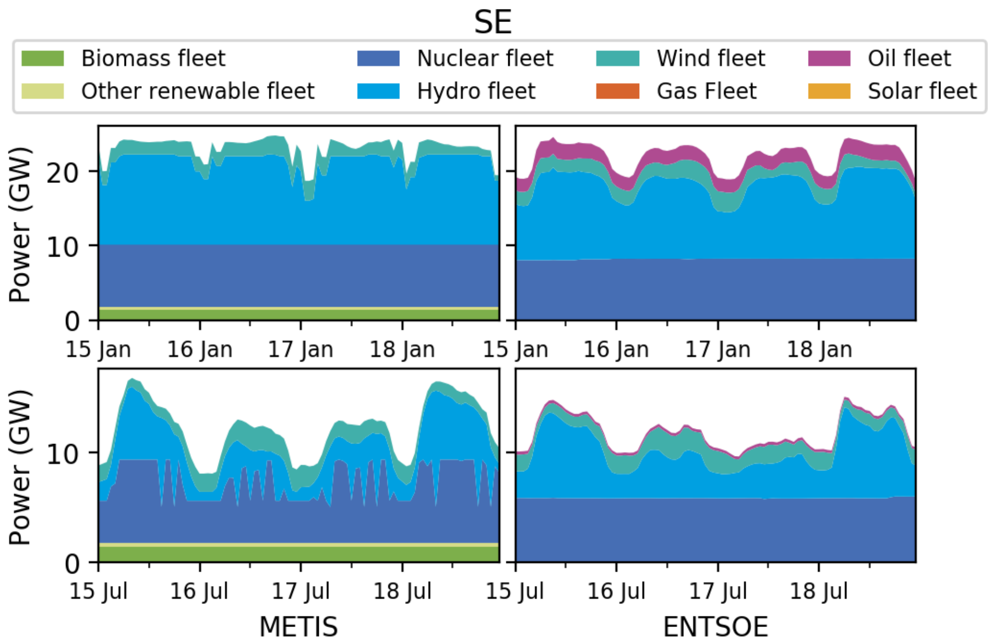

DK
Biomass fleet
Gas Fleet
Other renewable fleet
Hydro fleet
Wind fleet
Solar fleet
Coal fleet
Oil fleet
Power (GW)
0.0
2.5
5.0
15 Jan
16 Jan
17 Jan
18 Jan
Power (GW)
0
2
4
15 Jul
16 Jul
17 Jul
18 Jul
METIS
ENTSOE

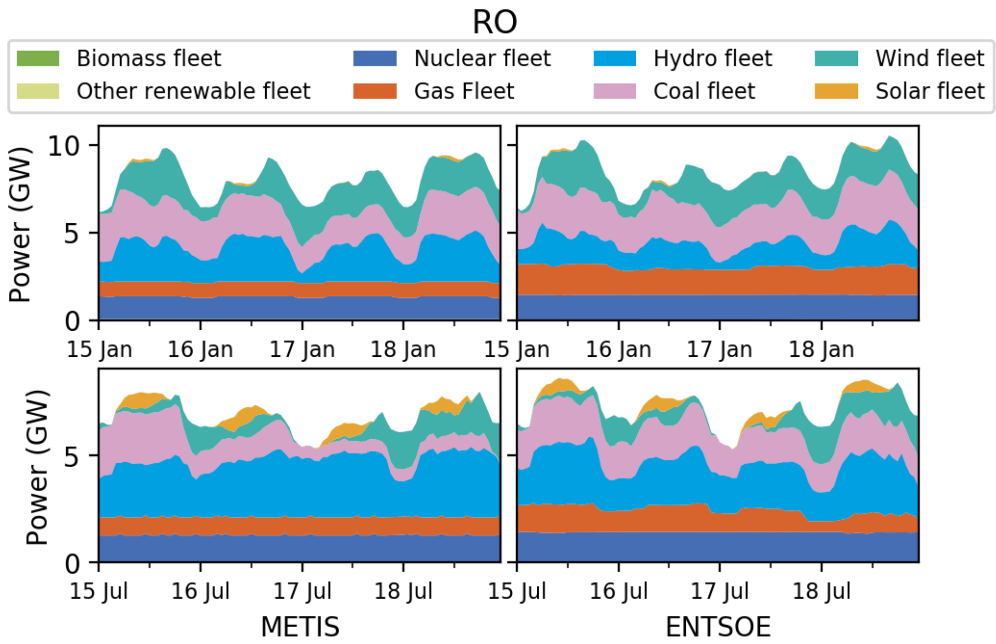


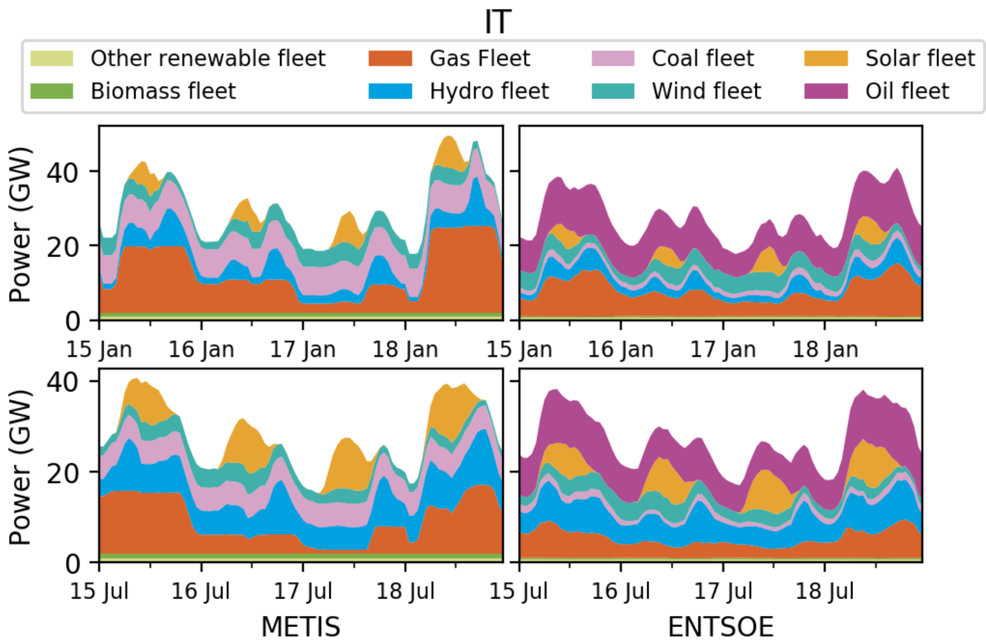
Note : Coal is lignite

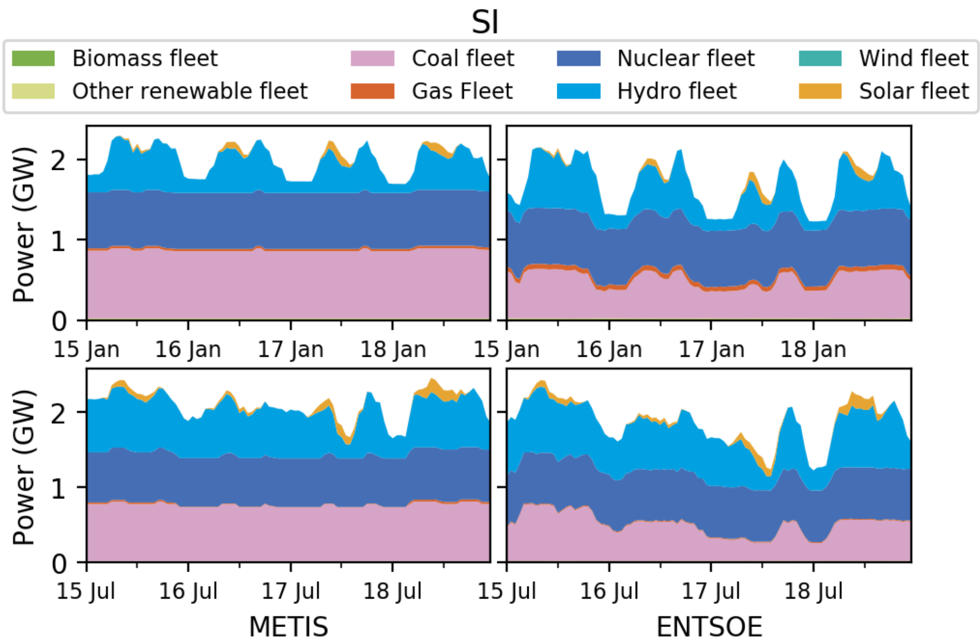


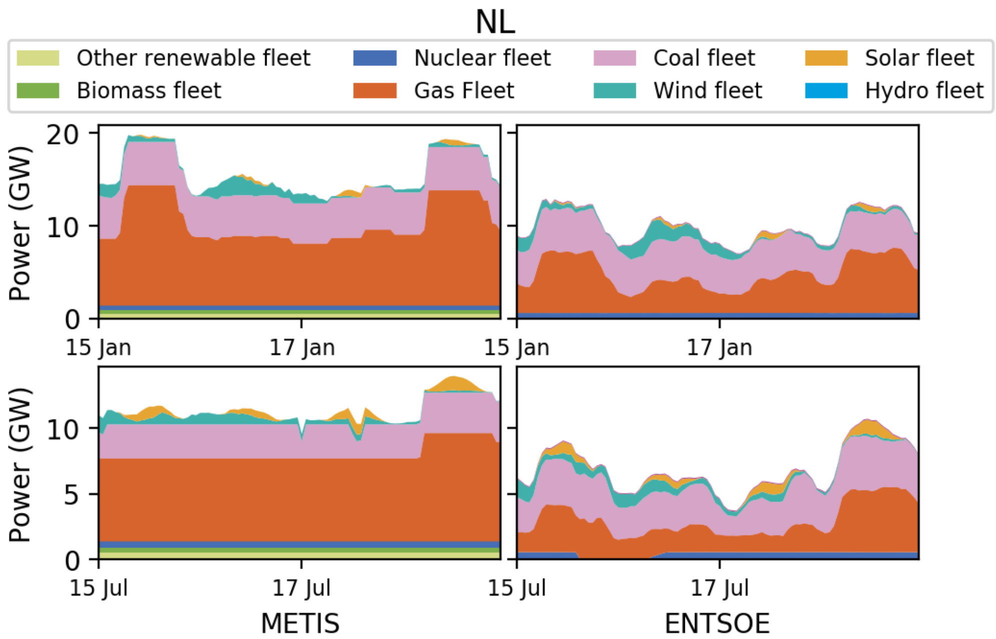

HU
Biomass fleet
Other renewable fleet
Nuclear fleet
Gas Fleet
Coal fleet
Hydro fleet
Oil fleet
Wind fleet
Solar fleet
Power (GW)
0
2
4
15 Jan
16 Jan
17 Jan
18 Jan
15 Jul
16 Jul
17 Jul
18 Jul
METIS
ENTSOE


SE
Biomass fleet
Other renewable fleet
Nuclear fleet
Hydro fleet
Wind fleet
Gas Fleet
Oil fleet
Solar fleet
Power (GW)
0
10
20
15 Jan
16 Jan
17 Jan
18 Jan
15 Jul
16 Jul
17 Jul
18 Jul
METIS
ENTSOE

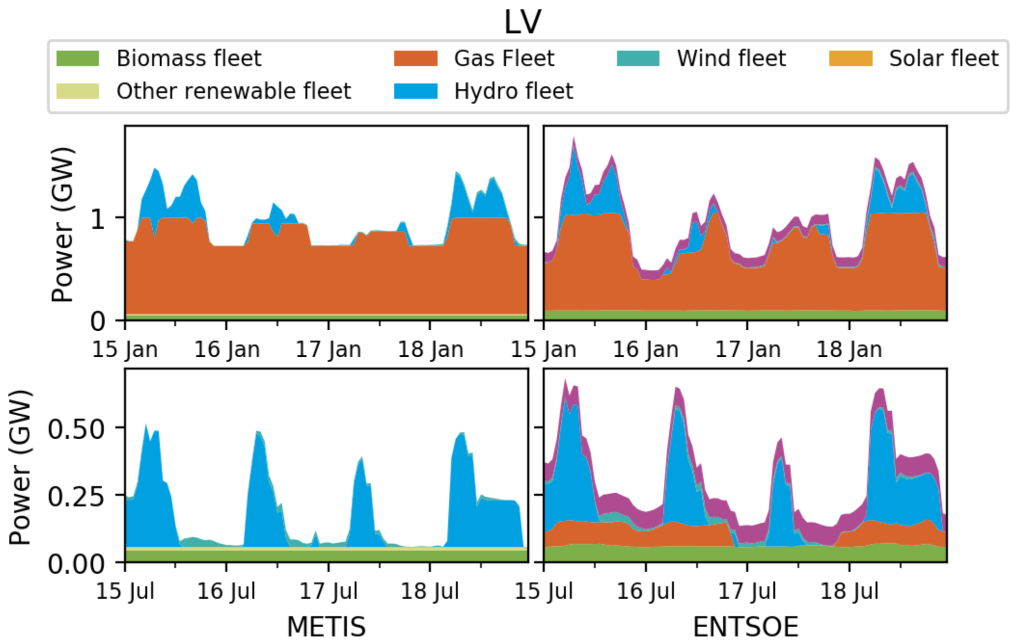

RO
Biomass fleet
Other renewable fleet
Nuclear fleet
Gas Fleet
Hydro fleet
Coal fleet
Wind fleet
Solar fleet
Power (GW)
0
5
10
15 Jan
16 Jan
17 Jan
18 Jan
15 Jul
16 Jul
17 Jul
18 Jul
METIS
ENTSOE

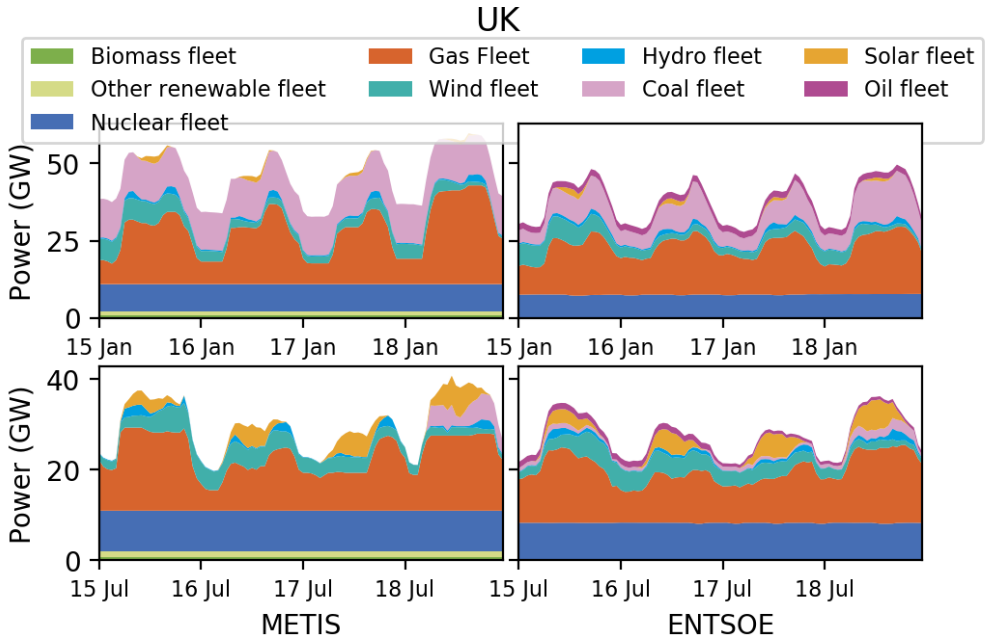

IT
Other renewable fleet
Biomass fleet
Gas Fleet
Hydro fleet
Coal fleet
Wind fleet
Solar fleet
Oil fleet
Power (GW)
0
20
40
15 Jan
16 Jan
17 Jan
18 Jan
15 Jul
16 Jul
17 Jul
18 Jul
METIS
ENTSOE





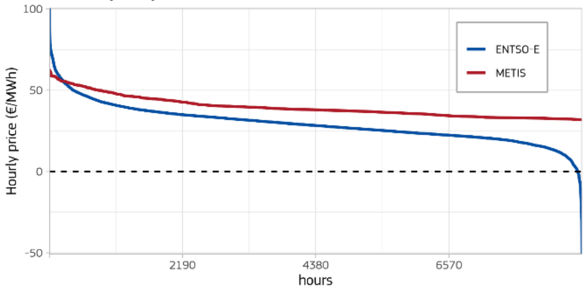
Note : ENTSOE hourly operation per type incomplete. Dispatching based on individual power plant operation which does not include smaller units.


LV
Biomass fleet
Gas Fleet
Wind fleet
Solar fleet
Other renewable fleet
Hydro fleet
Power (GW)
0
1
15 Jan
16 Jan
17 Jan
18 Jan
0.00
0.25
0.50
15 Jul
16 Jul
17 Jul
18 Jul
METIS
ENTSOE

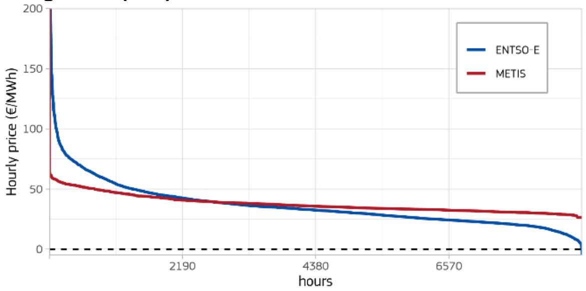

UK
Biomass fleet
Gas Fleet
Hydro fleet
Solar fleet
Other renewable fleet
Wind fleet
Coal fleet
Oil fleet
Nuclear fleet
Power (GW)
0
25
50
15 Jan
16 Jan
17 Jan
18 Jan
0
20
40
15 Jul
16 Jul
17 Jul
18 Jul
METIS
ENTSOE

Annex 9. Price duration curves

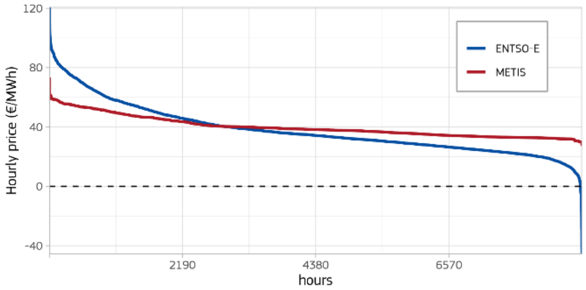
Austria (AT)



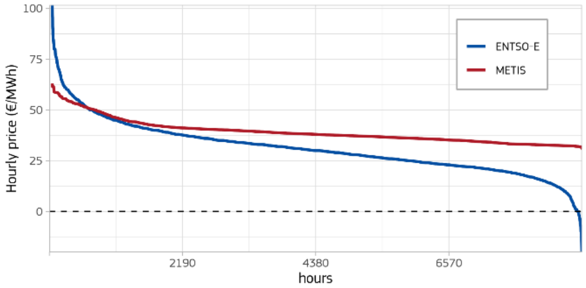
Belgium (BE)



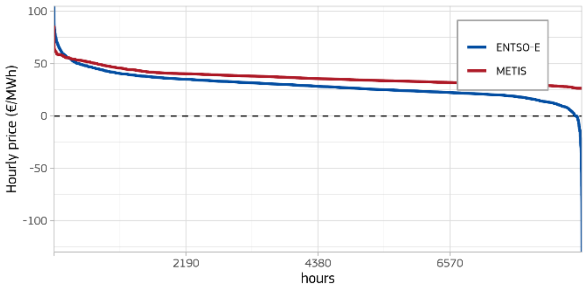
Switzerland (CH)



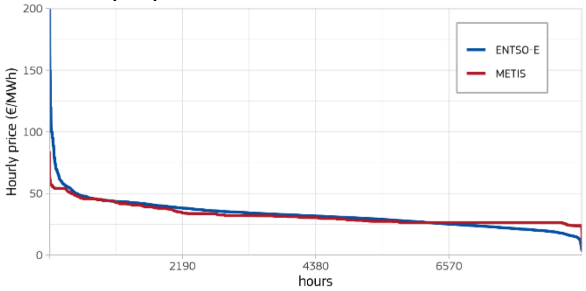
Czech Republic (CZ)



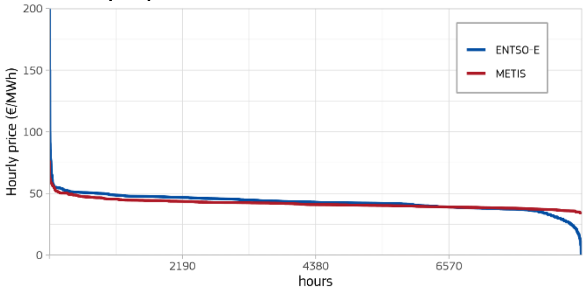
Germany (DE)



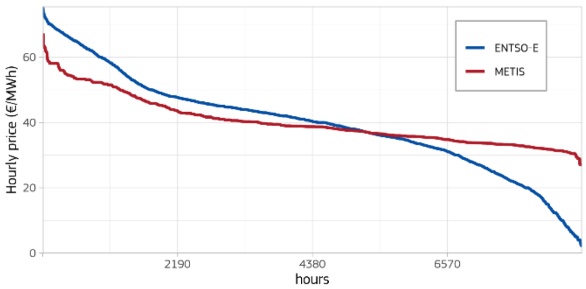
Estonia (EE)



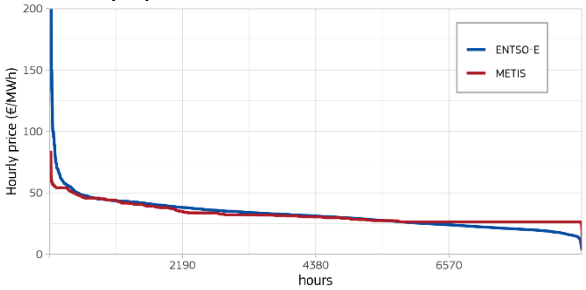
Greece (EL)



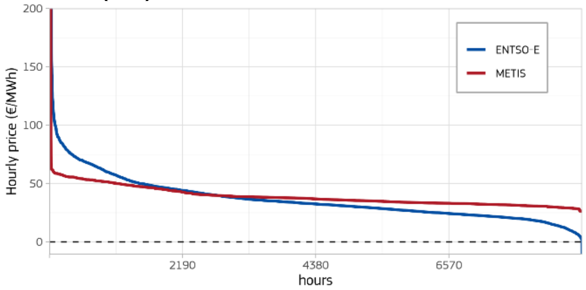
Spain (ES)



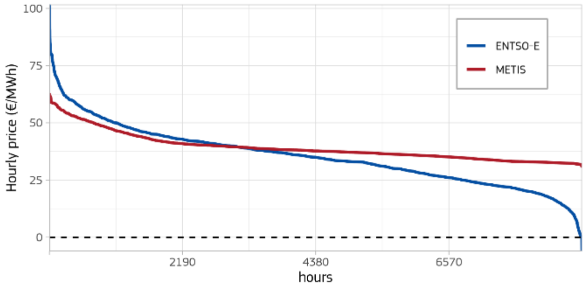
Finland (FI)



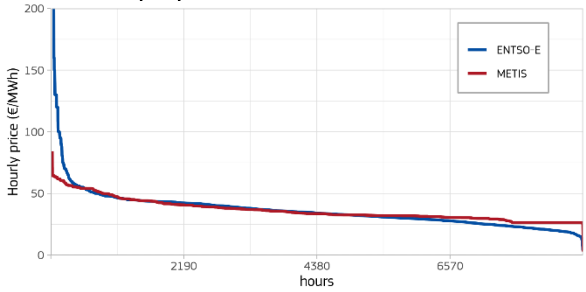
France (FR)



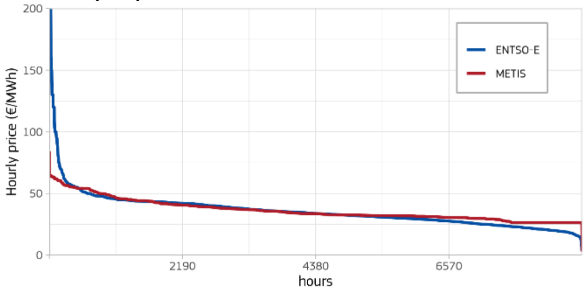
Hungary (HU)



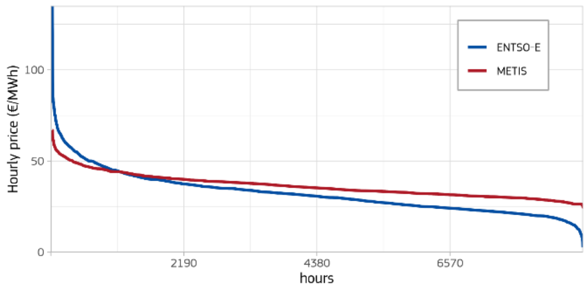
Lithuania (LT)



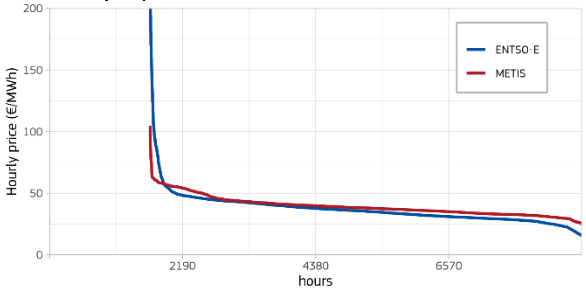
Latvia (LV)



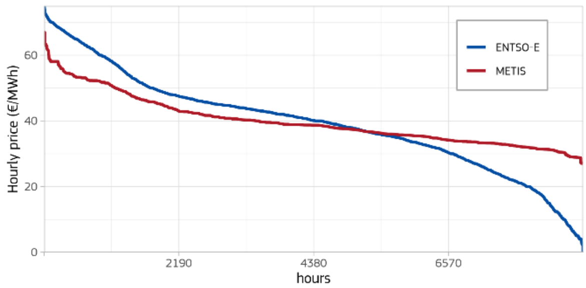
Netherlands (NL)



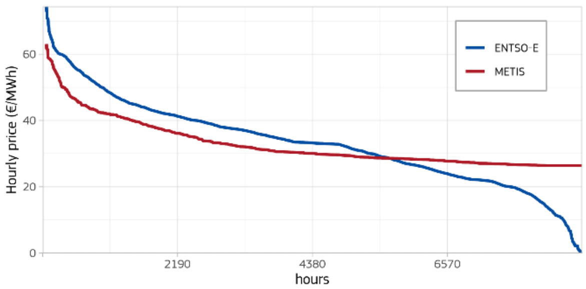
Poland (PL)



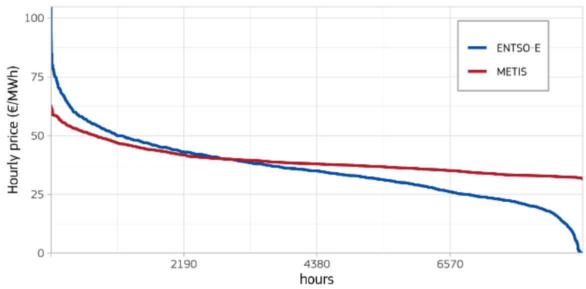
Portugal (PT)



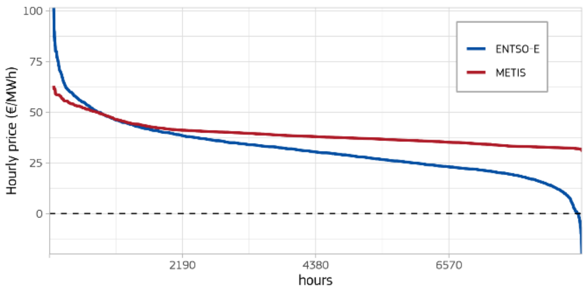
Romania (RO)



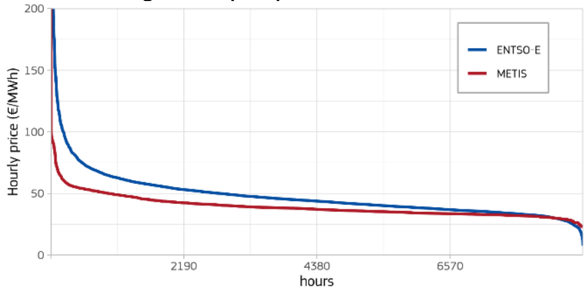
Slovenia (SI)



Slovakia (SK)



United Kingdom (UK)



Annex 10. Comparison of temporal features

Relative deviation (*RD*) of historical data with simulation results are presented in Figures 27 – 30 for different timeseries indicators (*i*). More specifically the following indicators are examined:

- Sum
- Average load
- Max load (99th percentile)
- Minimum load (2nd percentile)
- Maximum upwards ramp (98th percentile)
- Maximum downwards ramp (2nd percentile)
- Load factor (peakiness)

The indicator plotted is estimated by means of:

$$RD_i = \frac{Historical_{\,i} - METIS_i}{Historical_i}$$

Where *Historical* is the indicator (i) of the historical time series of any given country and technology and *METIS* is the indicator of simulated time series

Figure 27 shows three years (2016, 2017, and 2018) of historical power generation in Europe for different energy generation technologies and different countries that exist on both METIS and ENTSO-E datasets.

In order to compare the power plant fleets of METIS simulation with the historical results from ENTSOE transparency platform as presented in Figures 27 and 18, the following mapping was used:

Table 18 Mapping of power plant categories between METIS and ENTSOE TP

METIS	ENTSOE TP
Biomass fleet	Biomass
Coal fleet	[Fossil Coal-derived gas, Fossil Hard coal]
Fossil Gas ([OCGT, CCGT])	Fossil Gas
Geothermal fleet	Geothermal
Hydro RoR fleet	Hydro Run-of-river and poundage
Hydro fleet	Hydro Water Reservoir
Lignite fleet	[Fossil Brown coal/Lignite, Fossil Peat]
Nuclear fleet	Nuclear
Oil fleet	[Fossil Oil, Other]
Oil shale fleet	Fossil Oil shale
Other renewable fleet	[Marine, Other renewable]
Pumped storage fleet	Hydro Pumped Storage
Solar fleet	Solar
Waste fleet	Waste
Wind offshore fleet	Wind Offshore
Wind onshore fleet	Wind Onshore

Figure 31 Relative difference of energy generated annually per technology and country between historical and simulated results

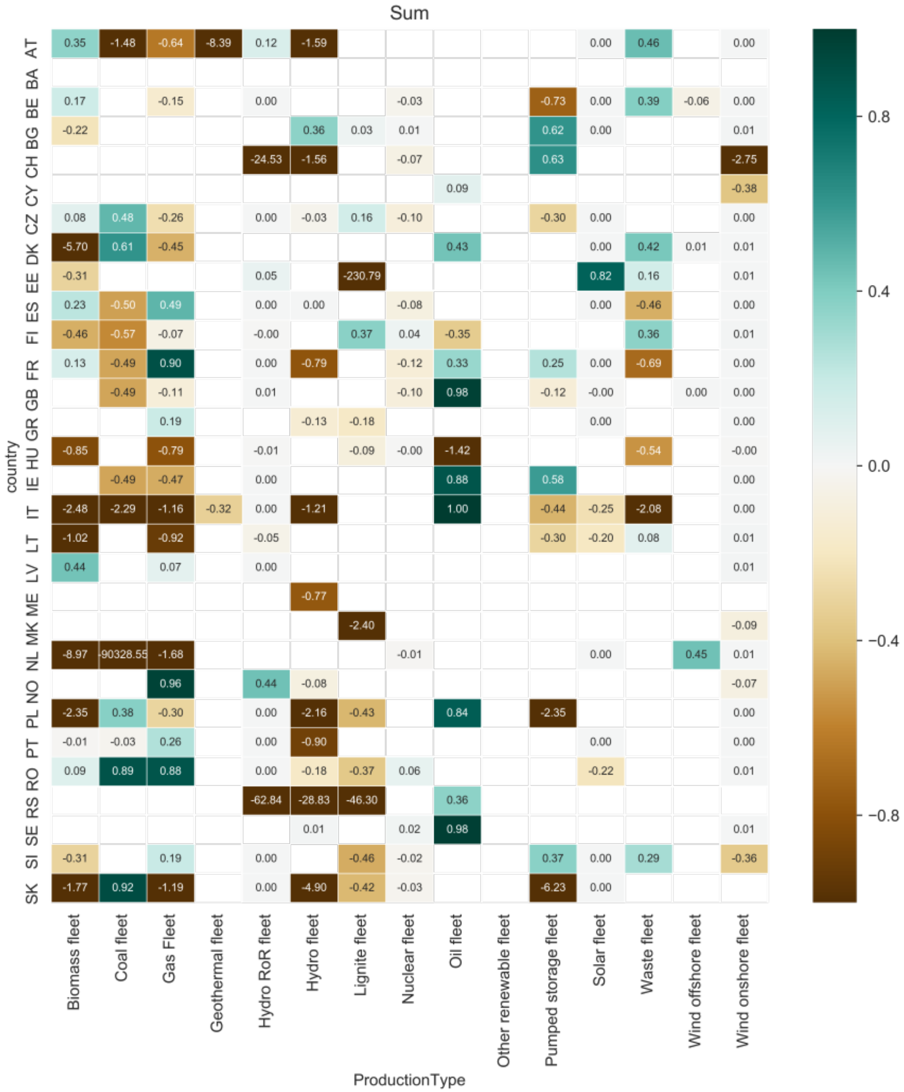


Figure 32: Relative difference of (a) minimum (represented as the 2nd percentile) and (b) maximum amount of energy generated annually per technology and country between historical and simulated results

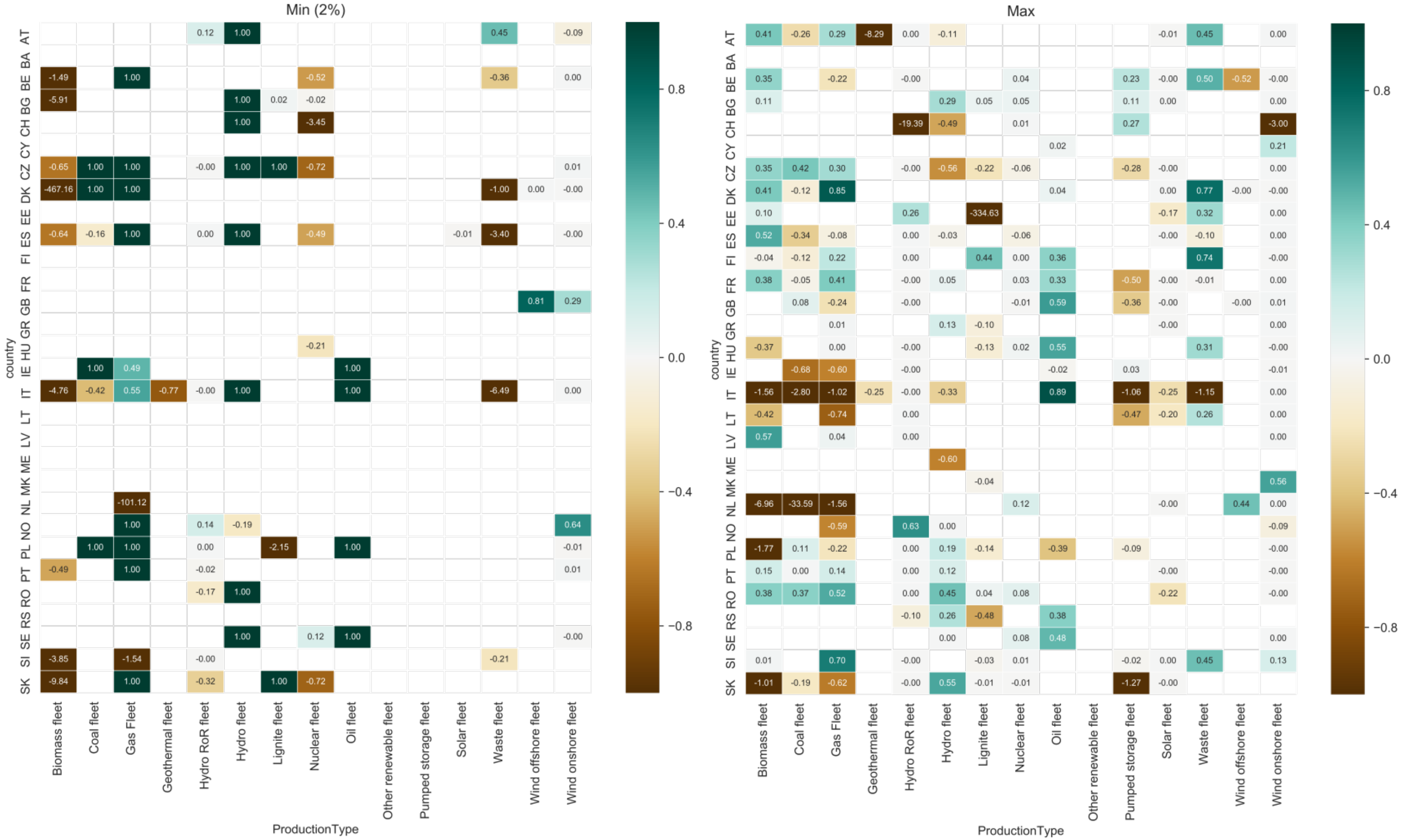
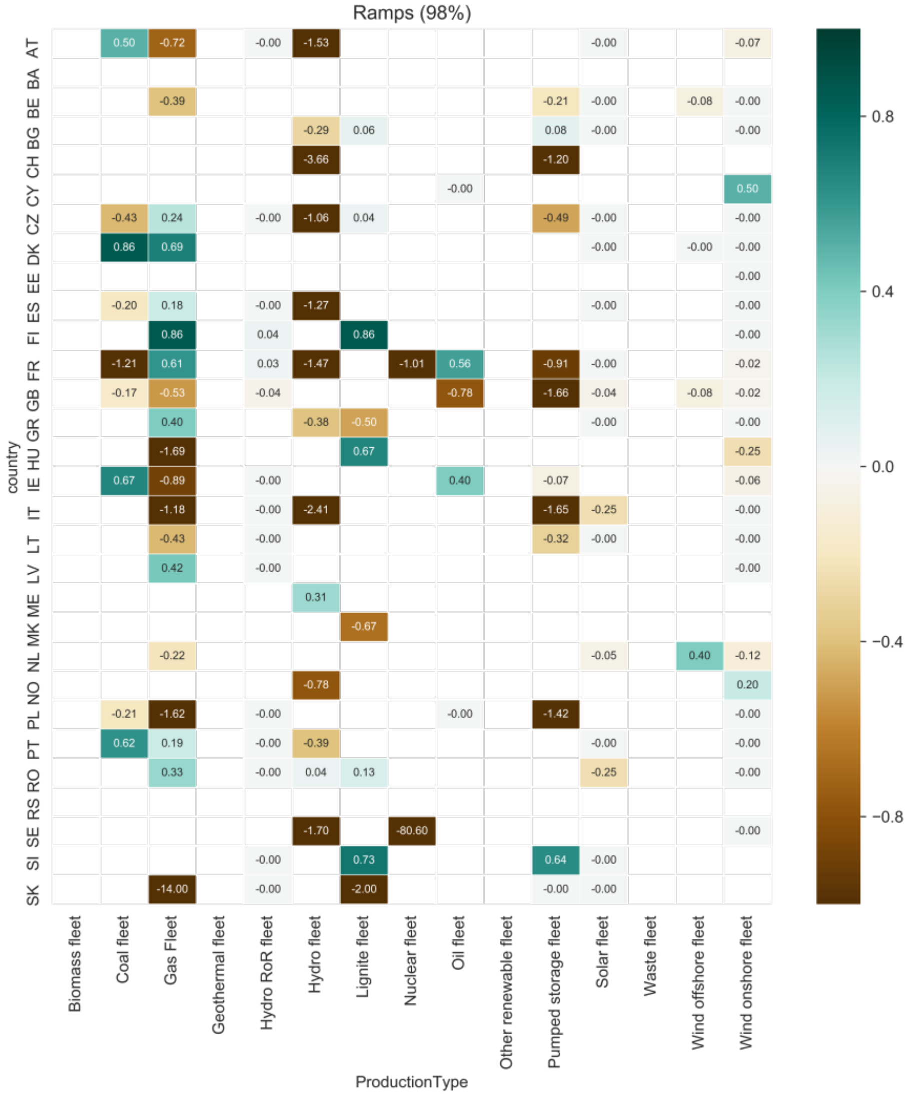


Figure 33 Relative difference of (a) largest positive load change (represented as the 98th percentile) and (b) largest negative load change (represented as the 2nd percentile) per technology and country between historical and simulated results



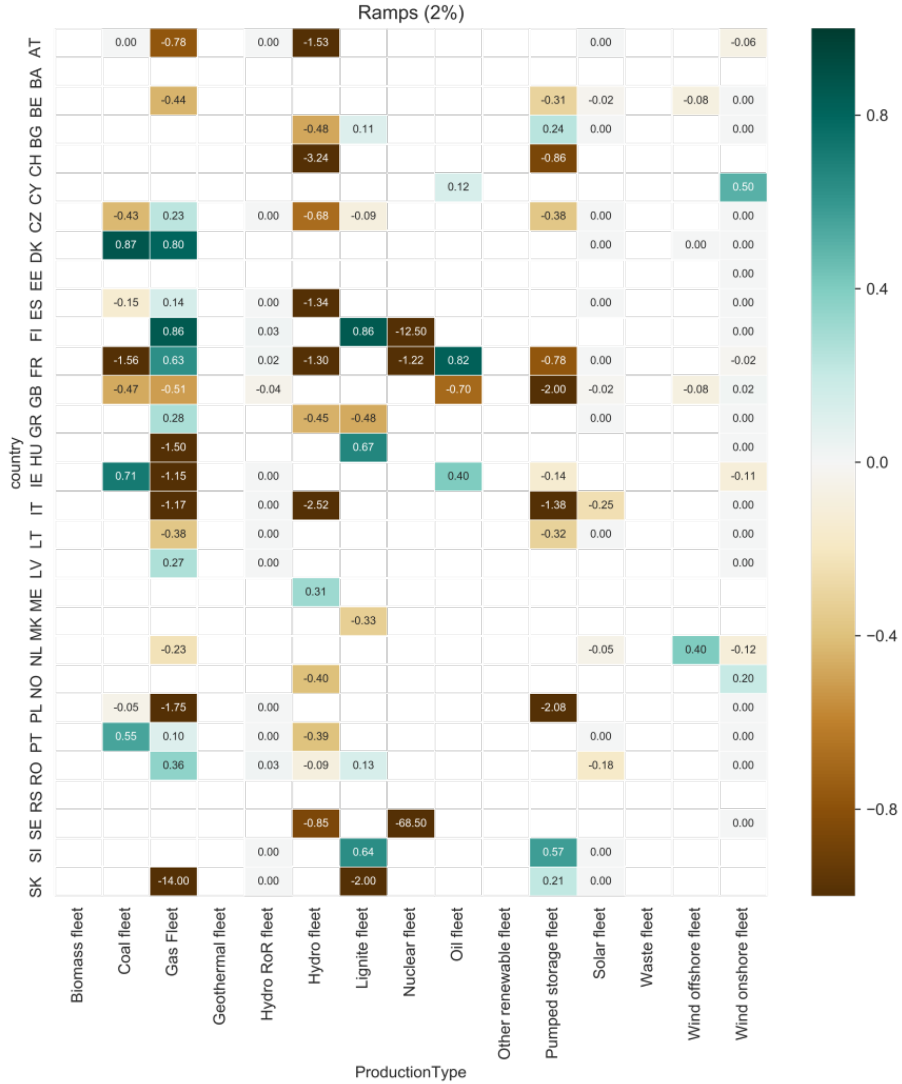


Figure 34 Relative difference of load factors between historical and simulated results per technology and country

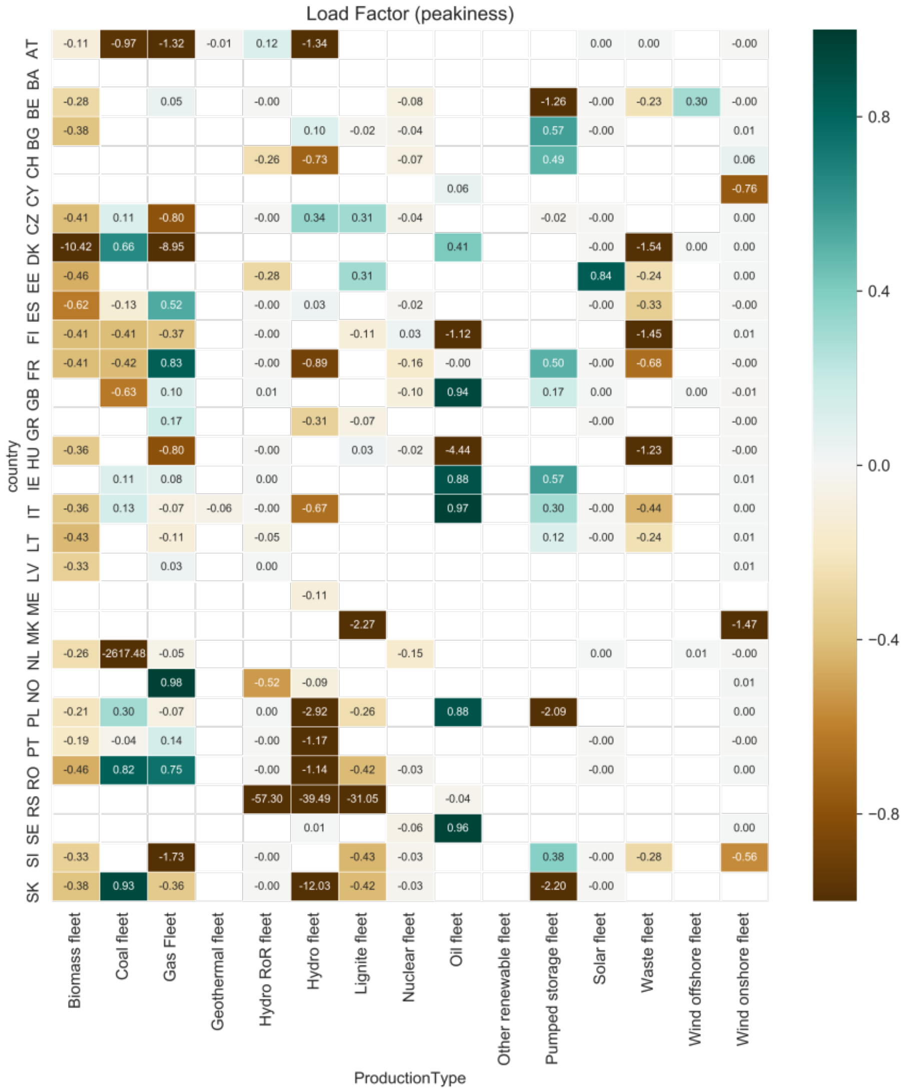
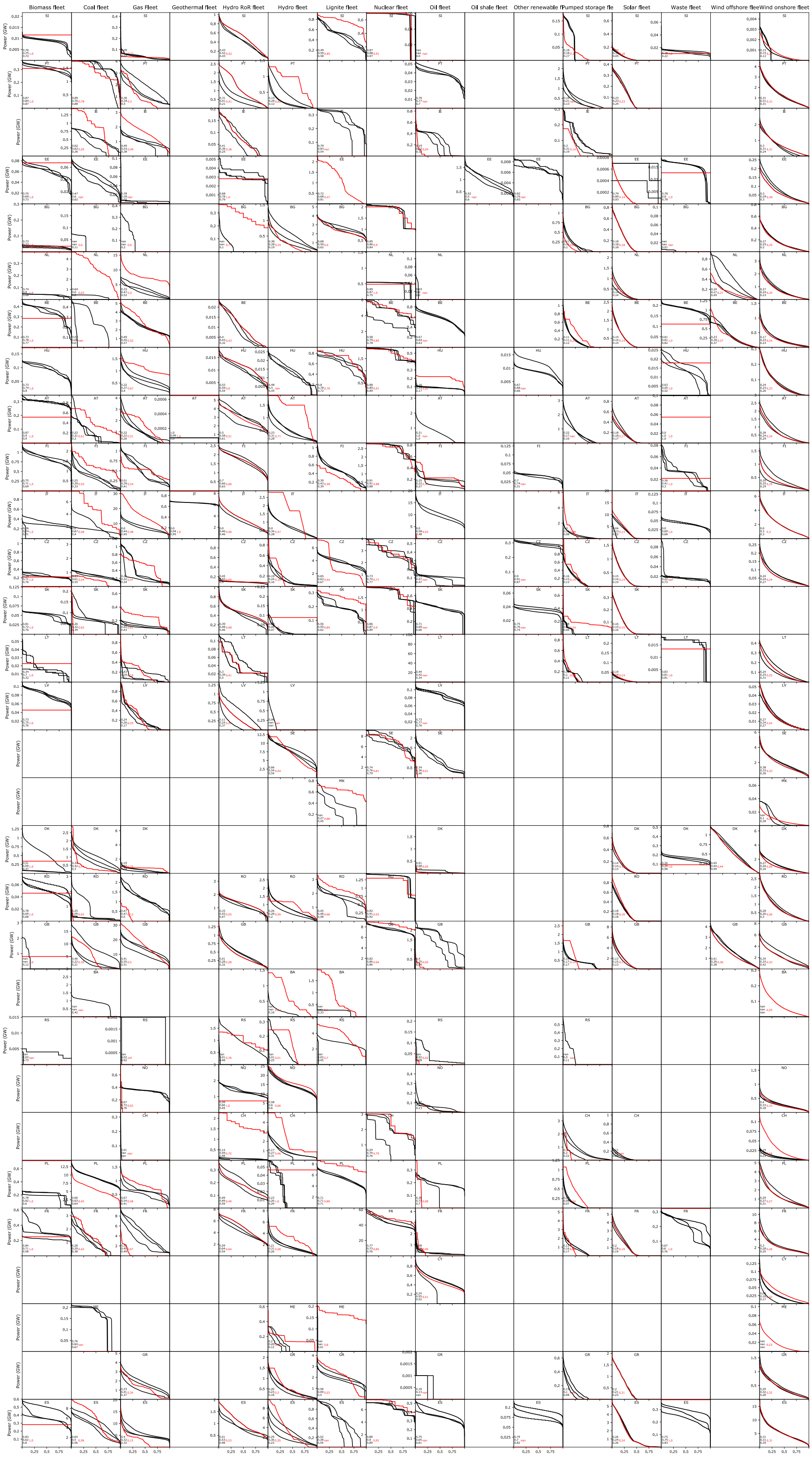


Figure 35 Power plant generation per technology and per country in the form of load duration curves. Simulation results are shown in red. Historical Load Duration curves per technology for EU countries for 2016–2018. The darker line corresponds to 2018.



KJ-NA-30008-EN-N

The European Commission's science and knowledge service

Joint Research Centre

JRC Mission

As the science and knowledge service of the European Commission, the Joint Research Centre's mission is to support EU policies with independent evidence throughout the whole policy cycle.

EU Science Hub
ec.europa.eu/jrc

@EU_ScienceHub

EU Science Hub - Joint Research Centre

EU Science, Research and Innovation

EU Science Hub

Publications Office of the European Union

doi:10.2760/434010

ISBN 978-92-76-14098-6